



Integrity ★ Service ★ Excellence

Atomic and Molecular Physics Program

7 March 2012

**Tatjana Curcic
Program Manager
AFOSR/RSE**

Air Force Research Laboratory

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2012 AFOSR SPRING REVIEW



NAME: Tatjana Curcic

BRIEF DESCRIPTION OF PORTFOLIO:

Understanding interactions between atoms, molecules, ions, and radiation.

LIST SUB-AREAS IN PORTFOLIO:

- **Cold Quantum Gases**
 - Strongly-interacting quantum gases
 - Ultracold molecules
 - New phases of matter
 - Non-equilibrium quantum dynamics
- **Quantum Information Science (QIS)**
 - Quantum simulation
 - Quantum communication
 - Quantum metrology, sensing, and imaging
 - Cavity optomechanics



Scientific and Transformational Opportunities



Scientific Opportunities	Transformational Opportunities
Dipolar Matter, Ultracold Molecules	• Novel phases of matter • Ultracold chemistry
Quantum Memories and Interfaces	• Long-distance quantum communication
Quantum Simulation	• High-T_c superconductivity • Novel phases of matter
Quantum Metrology and Sensing	• Ultra-high-precision clocks • High-resolution, high-sensitivity magnetometry • High-sensitivity gravimetry • Precision inertial navigation in GPS-denied environments
Non-equilibrium Quantum Dynamics	• Dynamic control of materials • Efficient optical devices





Outline



- **Quantum Simulation, Strongly-Interacting Quantum Gases**
 - **Bosons: Markus Greiner, Harvard (MURI)**
 - **Algorithmic Cooling in Quantum Gases**
Waseem Bakr, *et al*, *Nature* **480**, 500 (2011)
 - **Quantum Magnetism**
Jonathan Simon, *et al*, *Nature* **472**, 307 (2011)
 - **Fermions: Martin Zwierlein, MIT (PECASE, MURI)**
 - **Evolution of Fermi Pairing from 3D to 2D**
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 - **Thermodynamics of a Unitary Fermi Gas: Superfluid Lambda Transition**
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 - **Dy BEC, and First Dipolar Degenerate Fermi Gas**
Mingwu Lu, *et al*, *Phys. Rev. Lett.* **107**, 190401 (2011)
- **Quantum Metrology: Till Rosenband, NIST**
 - **Coherent Drive Spectroscopy**
D.B. Hume, *et al*, *Phys. Rev. Lett.* **107**, 243902 (2011)

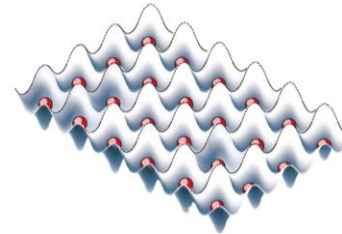


Strongly-correlated quantum gases



Optical lattices

Atoms interact strongly on lattice sites
Superfluid - Mott insulator transition

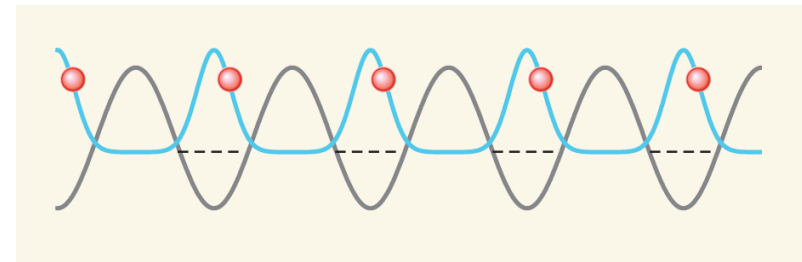
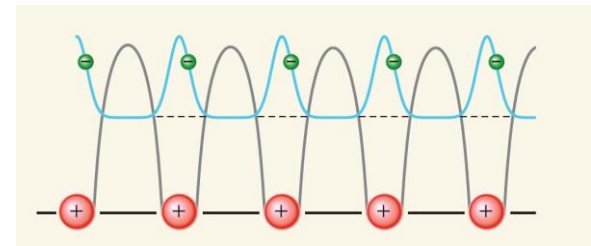


Synthetic matter, quantum simulations

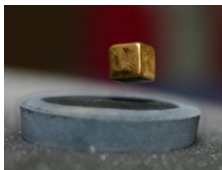
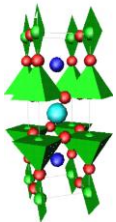
Electrons in a crystal lattice



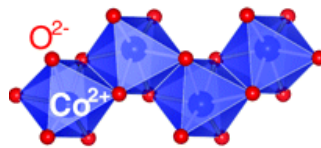
Atoms in an optical lattice



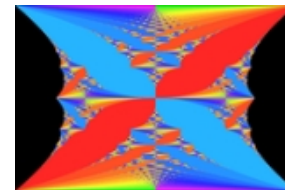
Strongly correlated materials



High Tc superconductors



Quantum magnets



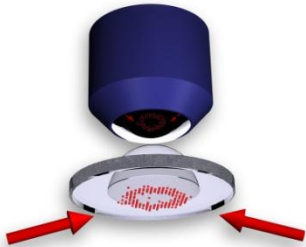
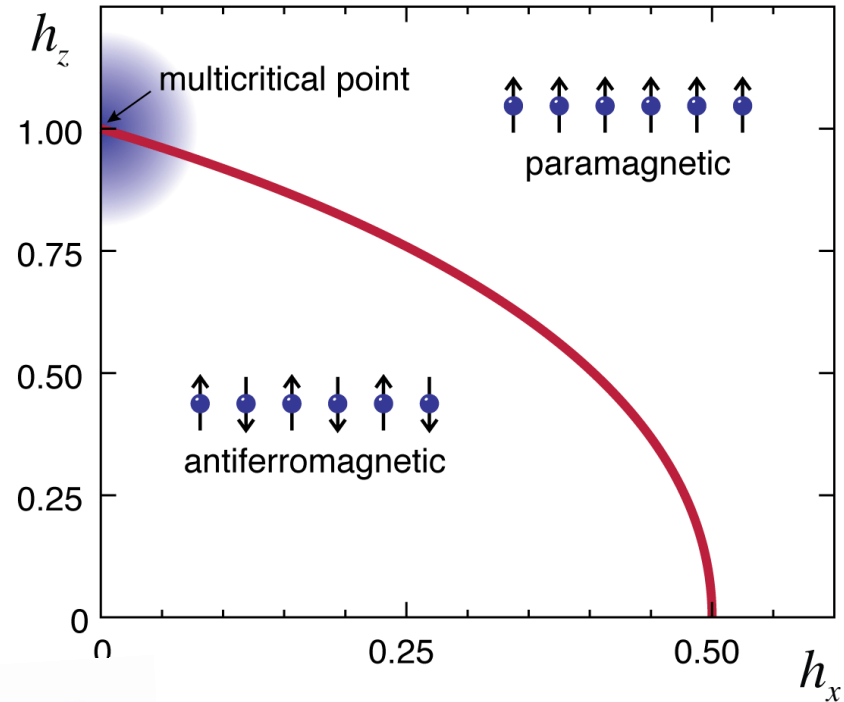
Quasi-low
dimensional
materials



Quantum magnetism



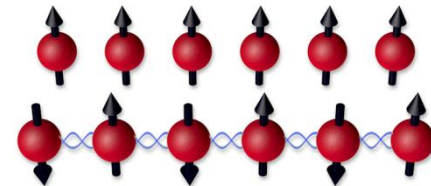
Ising model:
*quantum phase transition
from paramagnet to
antiferromagnet*



**Quantum gas
microscope**



**Algorithmic
cooling**



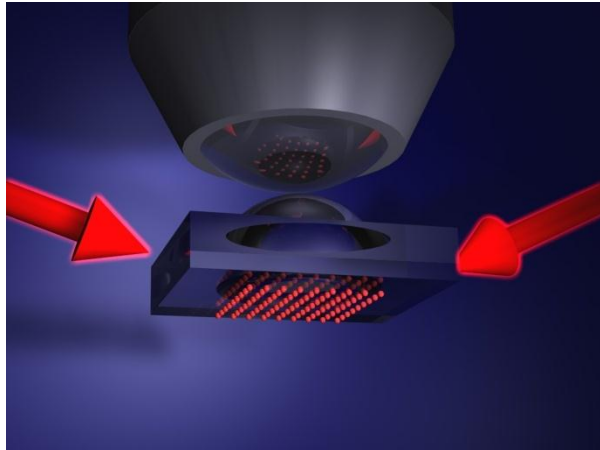
**Quantum
magnetism**



Quantum Gas Microscope

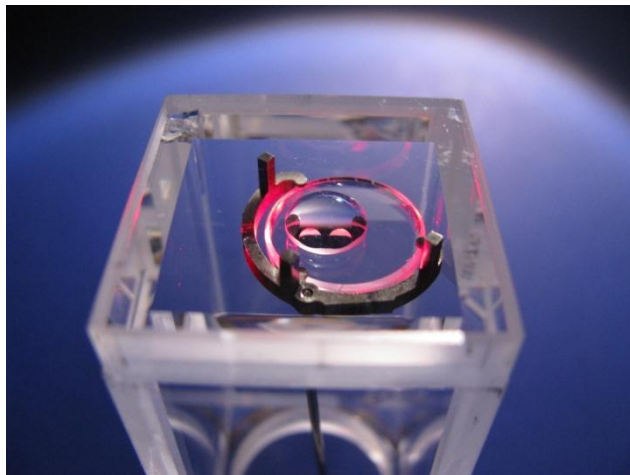
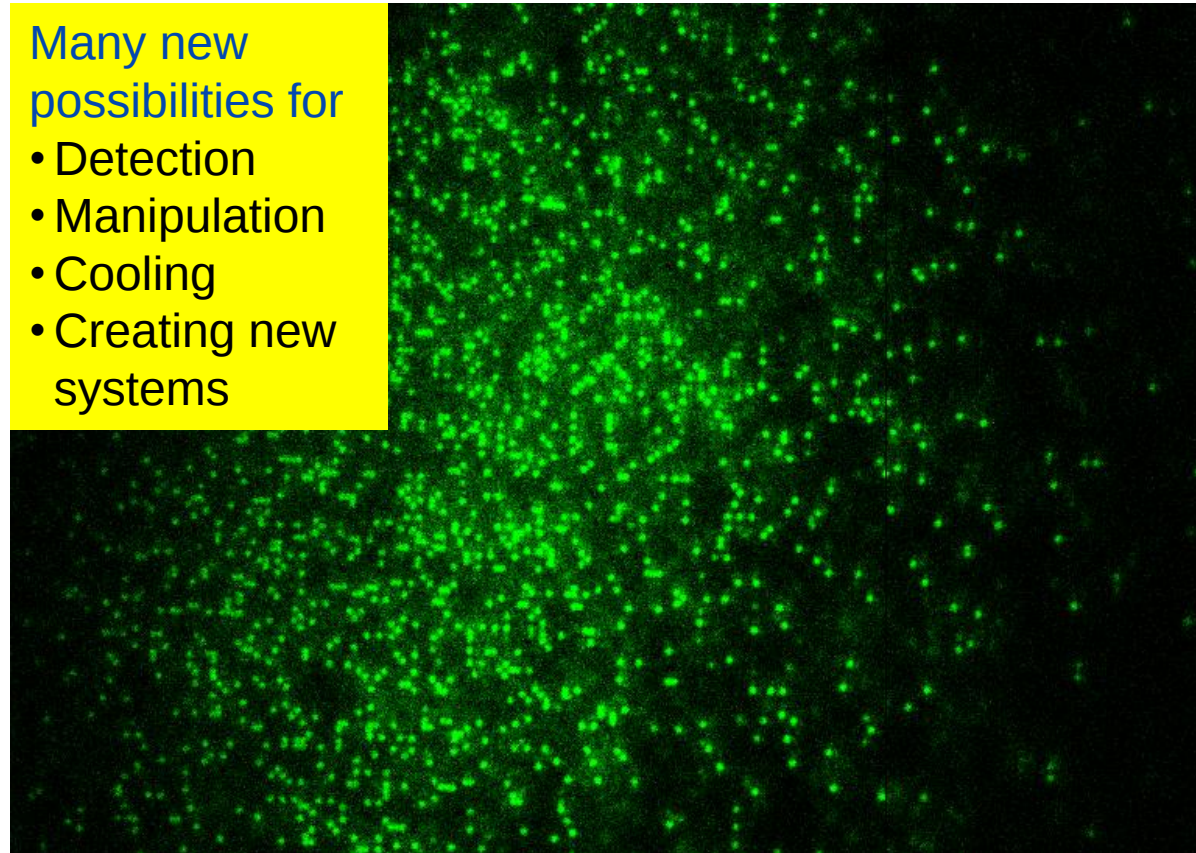


Waseem S. Bakr, *et al*, *Nature* **463**, 74 (2009)



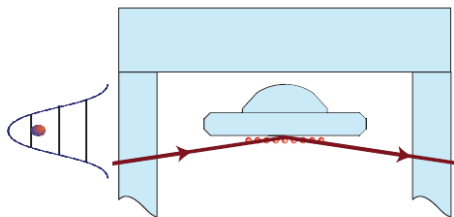
Many new possibilities for

- Detection
- Manipulation
- Cooling
- Creating new systems





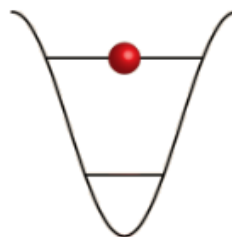
Interaction induced orbital excitation blockade



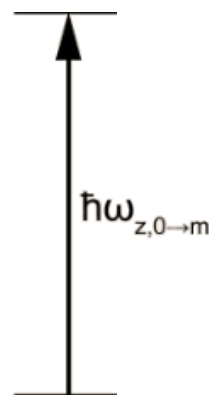
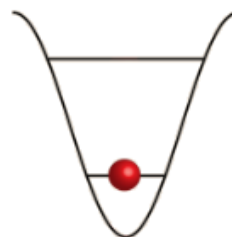
Axial vibrational excitation

$$|n_{\text{ground}}, n_{\text{excited}}\rangle$$

$$|0, 1\rangle$$



$$|1, 0\rangle$$

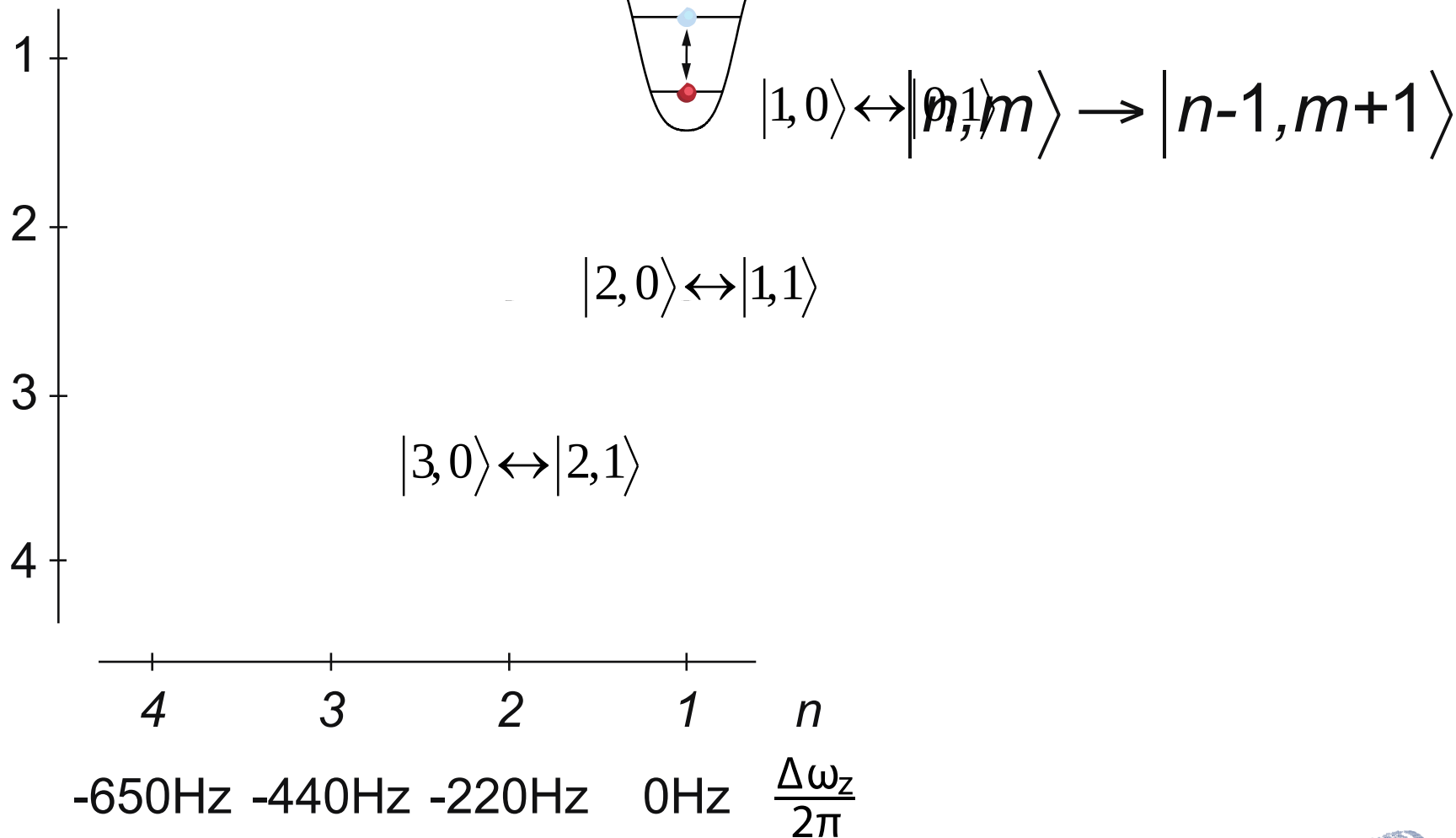




Orbital excitation blockade operations



$$n_{tot} = n + m$$





Algorithmic cooling



Random occupation



Filter operations

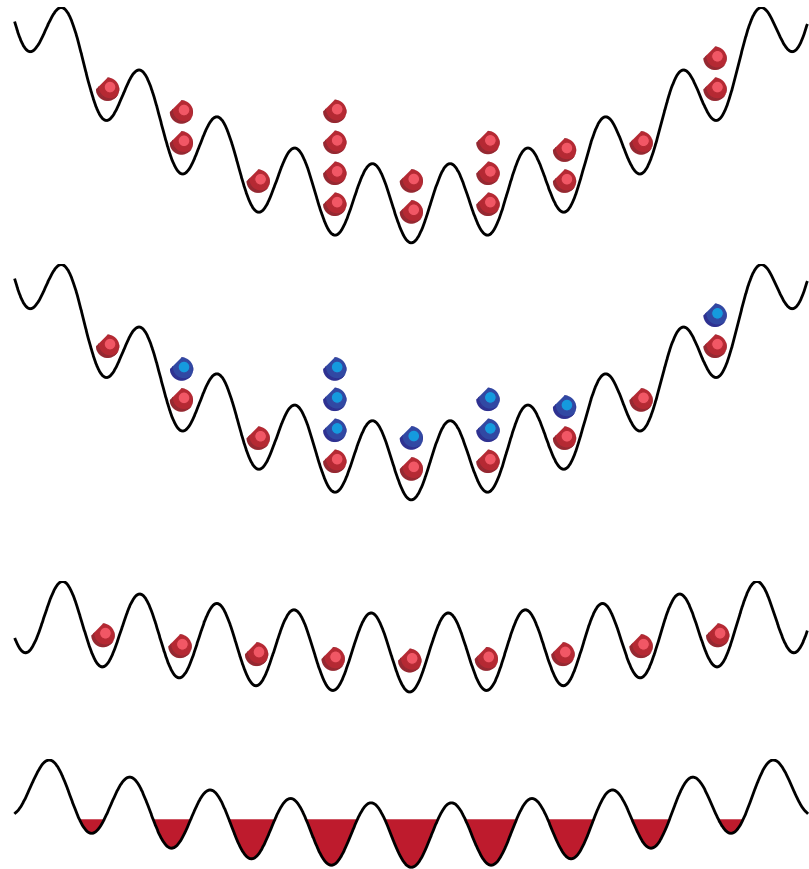
$4 \rightarrow 3$, $3 \rightarrow 2$, $2 \rightarrow 1$



Mott insulator

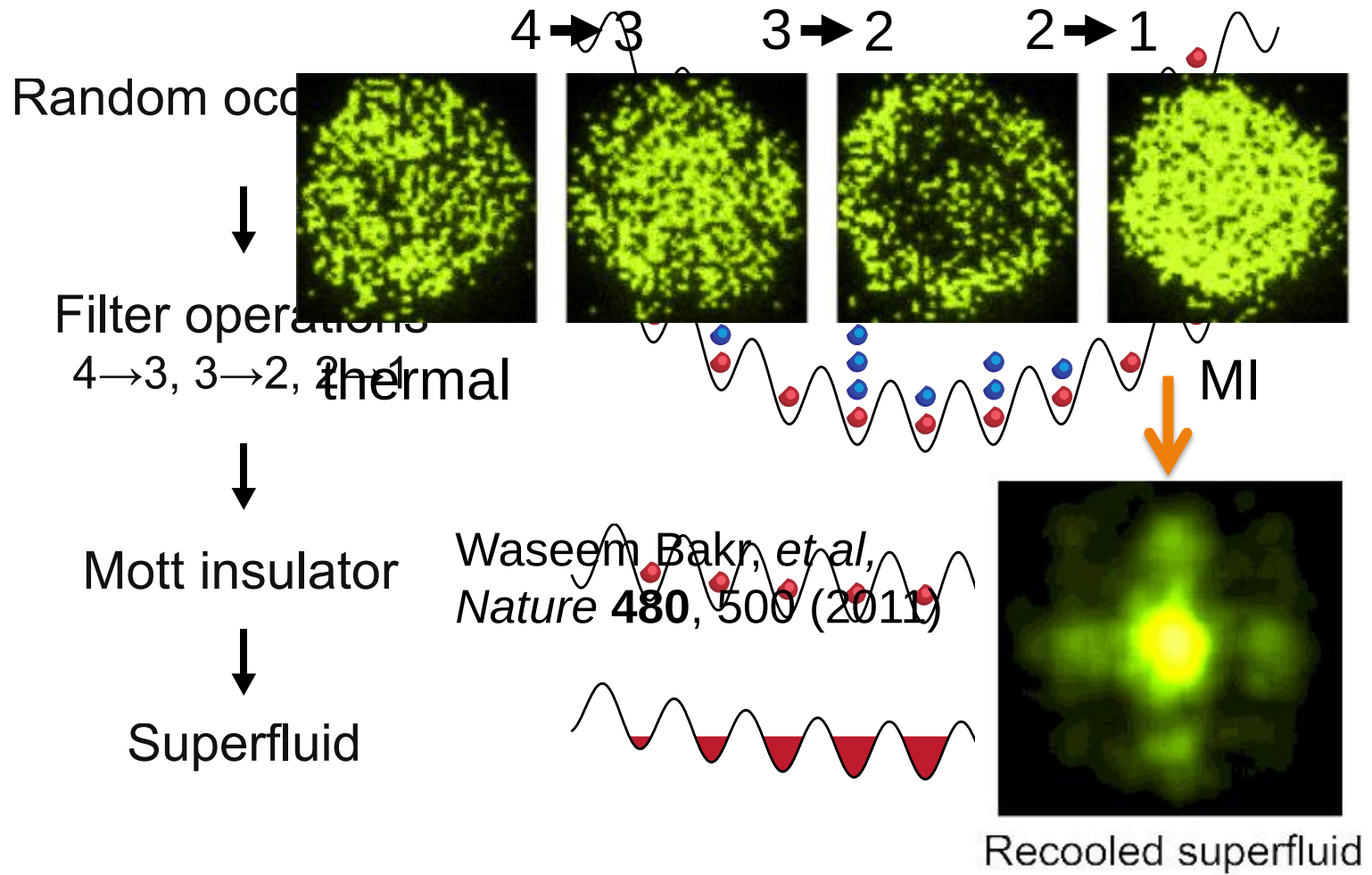


Superfluid





Algorithmic cooling

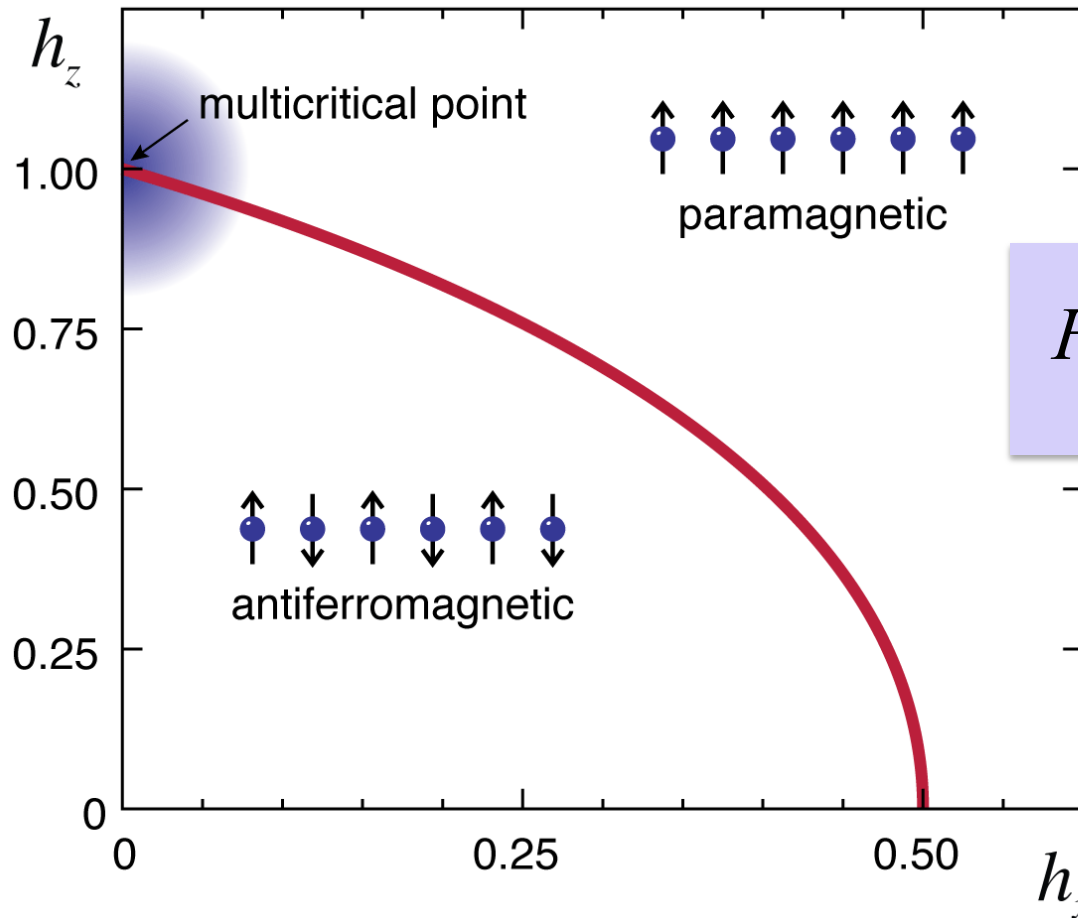




Quantum Magnetism



Quantum simulation of an antiferromagnetic Ising spin chain



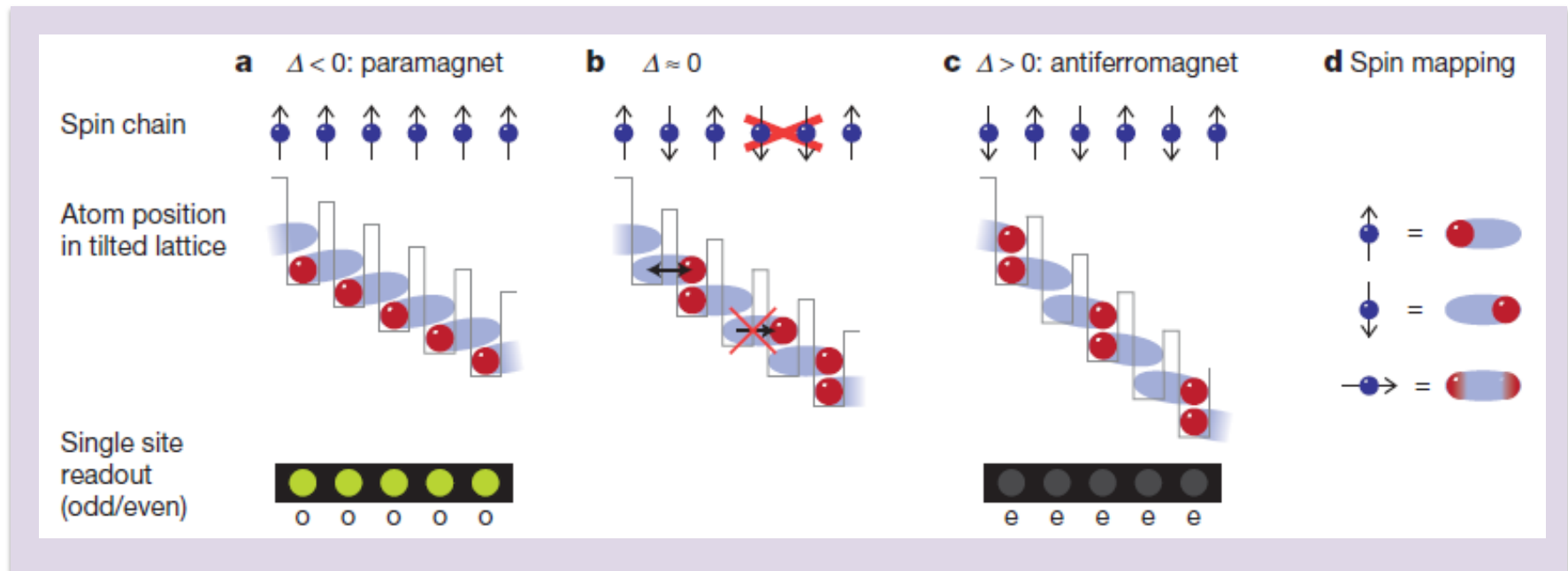
$$H = J \sum_i S_z^i S_z^{i+1} - h_z S_z^i - h_x S_x^i$$

$h_x = 0$: classical first order phase transition

Finite h_x : quantum phase transition, second order



Tilted Hubbard Model and Mapping to Spin Model



realizes constraint *drives transition*

$$H = J \sum_i \overbrace{S_z^i S_z^{i+1}}^{h_z} - \underbrace{(1 - \tilde{D}) S_z^i}_{h_x} - \underbrace{2^{3/2} \tilde{t} S_x^i}_{h_x}$$

$$D = E - U$$

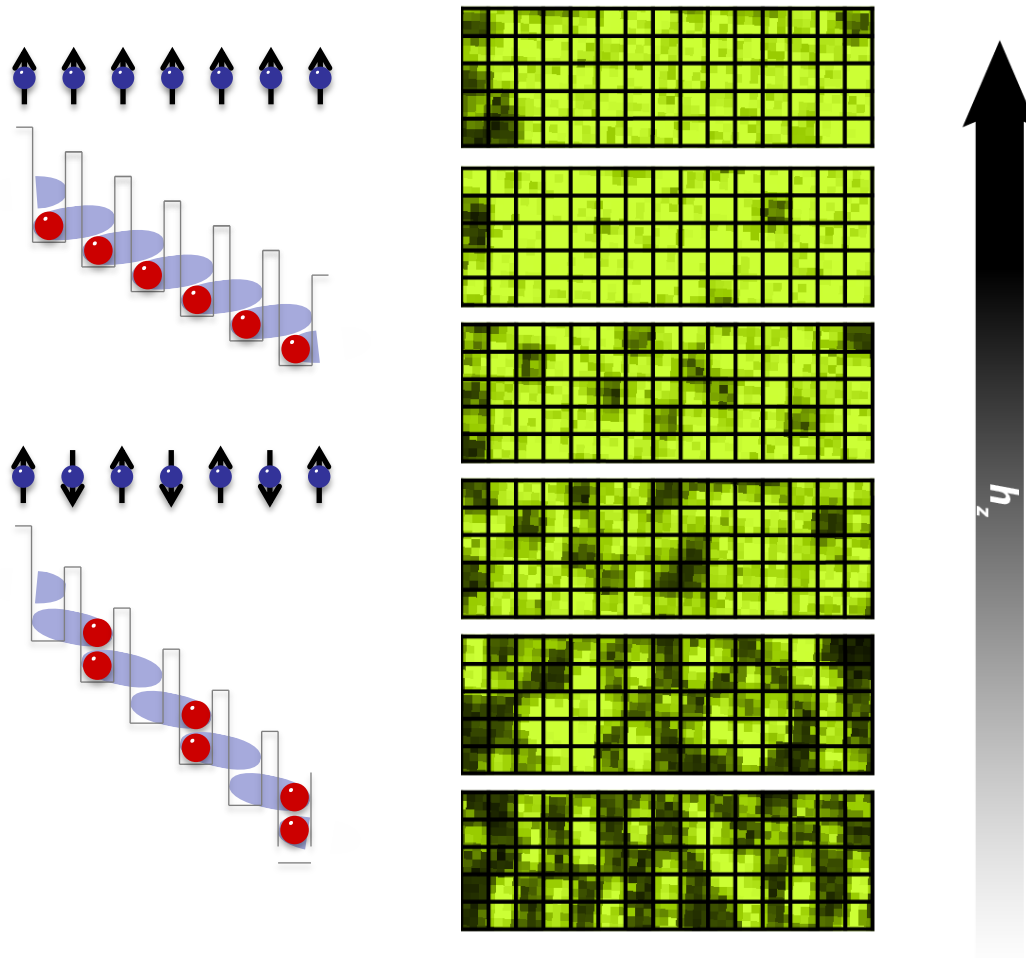
E: energy difference per lattice site, or lattice tilt
U: onsite interaction



Adiabatic transition to the AF state



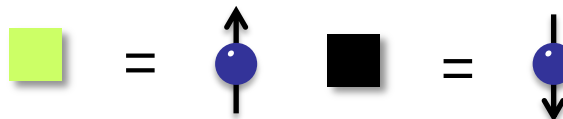
Jonathan Simon, *et al*, *Nature* **472**, 307 (2011)



- High magnetic field:
spins align with field

- Low magnetic field:
antiferromagnetic
interactions
dominate, producing
Neel order

Modulation spectroscopy:
turn double occupancy
into single occupancy

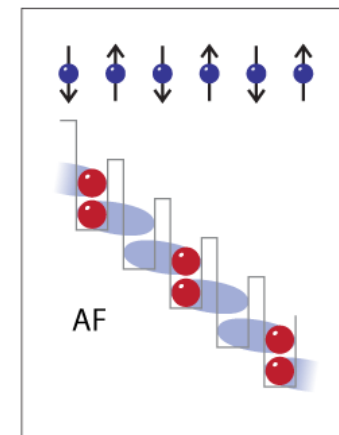
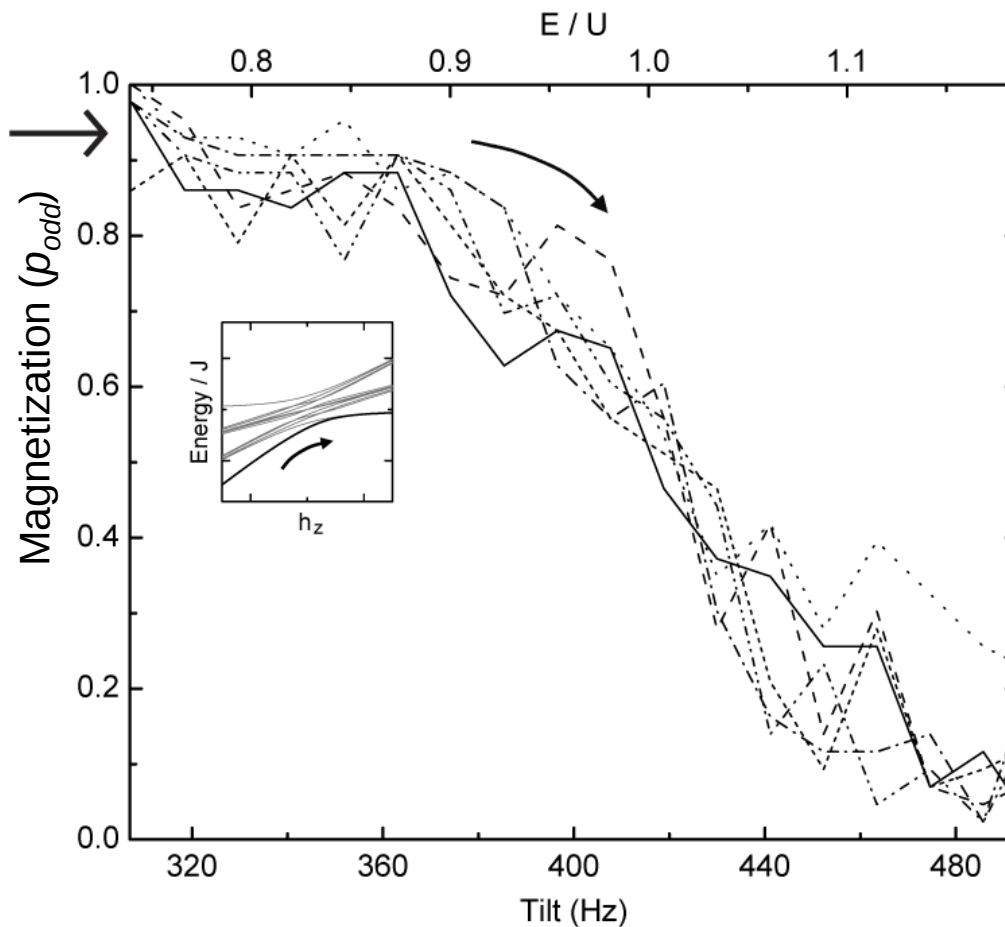
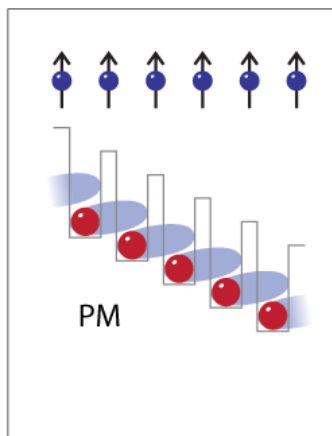


Direct spin imaging
preliminary





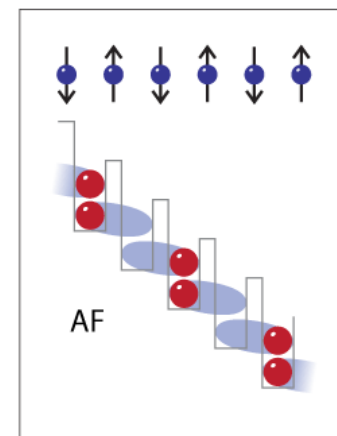
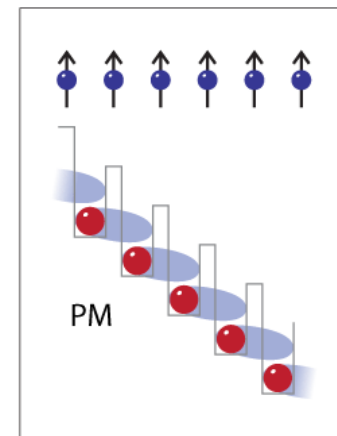
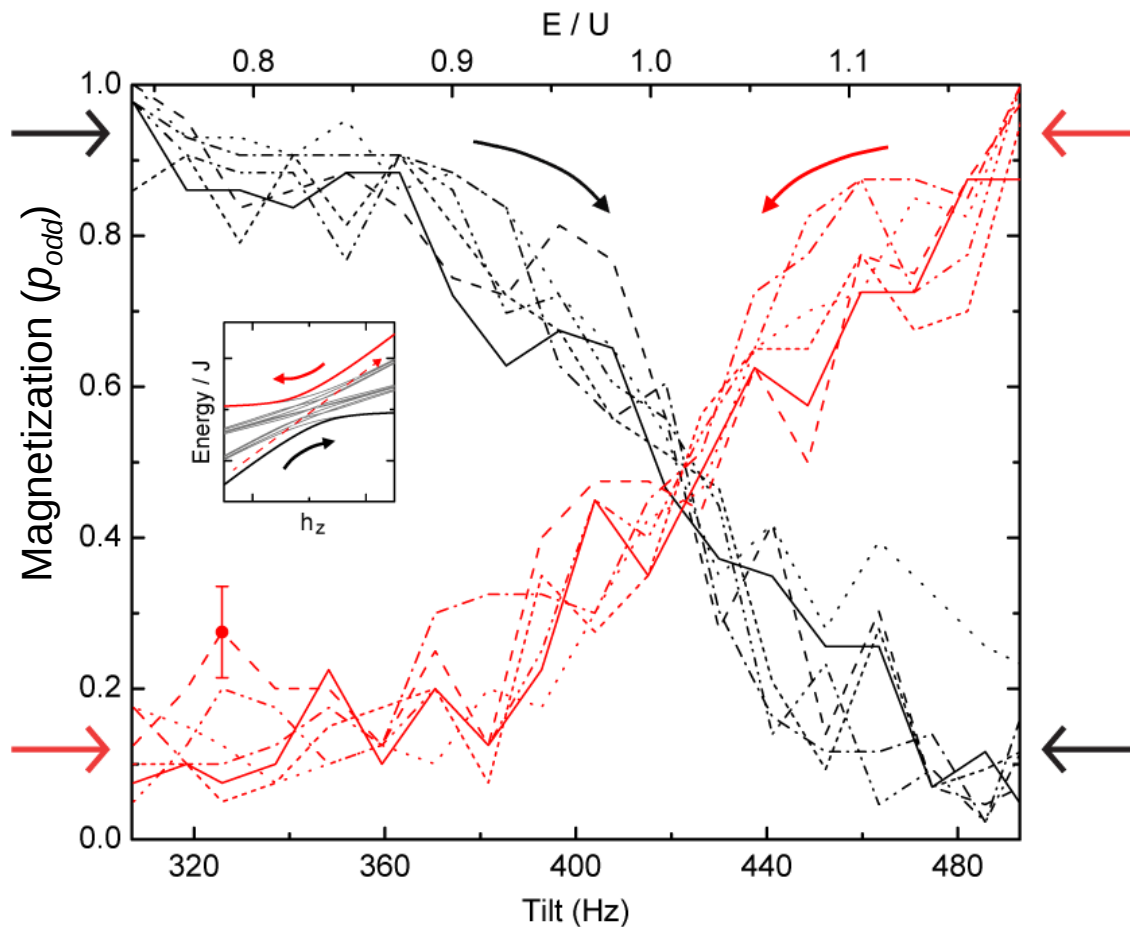
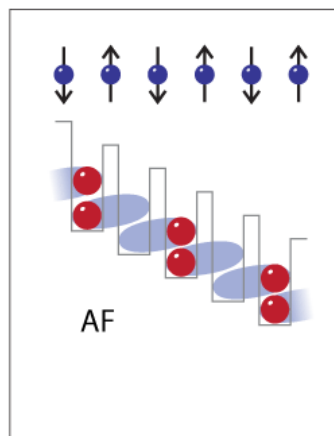
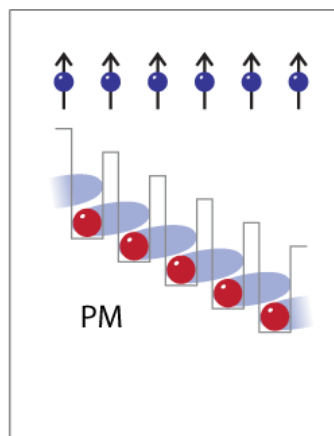
Selecting homogeneous domain



- 6 adjacent sites that transition simultaneously (RMS shift 6 Hz)
- Compare to 10%-90% width (105 Hz) and transverse field (28 Hz)



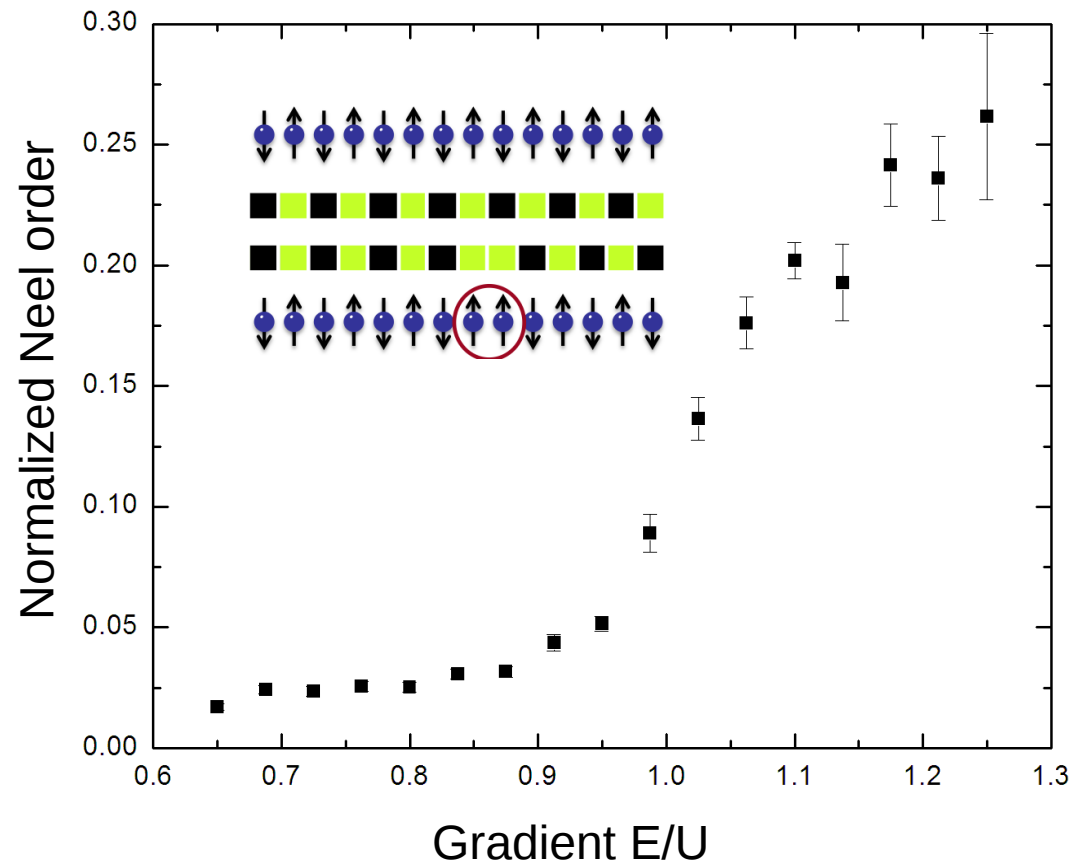
Transitioning at highest and lowest energy many-body state



Jonathan Simon, *et al*, *Nature* **472**, 307 (2011)



Direct measurement of Neel order parameter





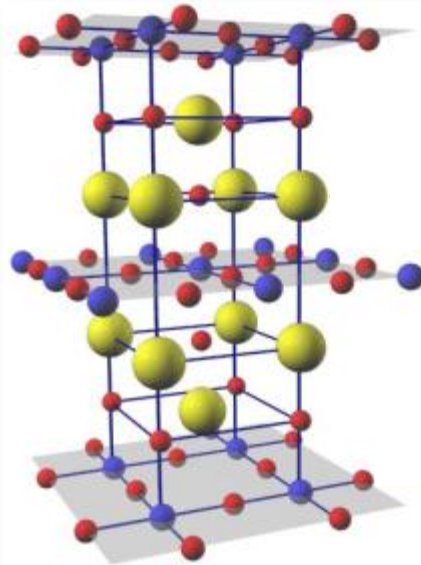
Outline



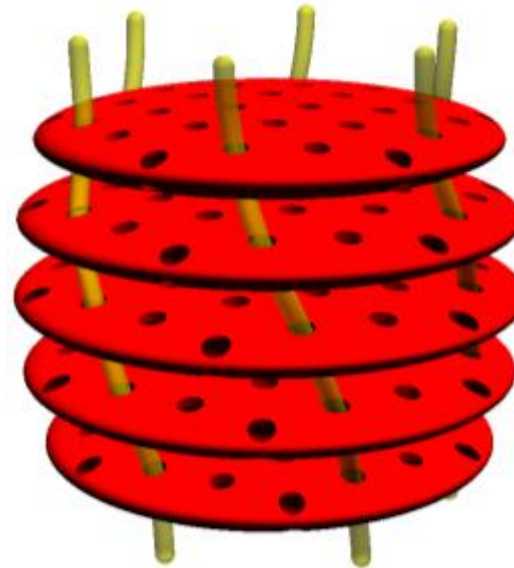
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Strongly Interacting Fermi Gases in coupled quasi-2D layers



**High- T_c Superconductor
with stacks of CuO planes**



**Stacks of 2D coupled
fermionic superfluids**

- Access physics of layered superconductors
- Evolution of Fermion Pairing from 3D to 2D
- Berezinskii-Kosterlitz-Thouless transition in deep 2D limit



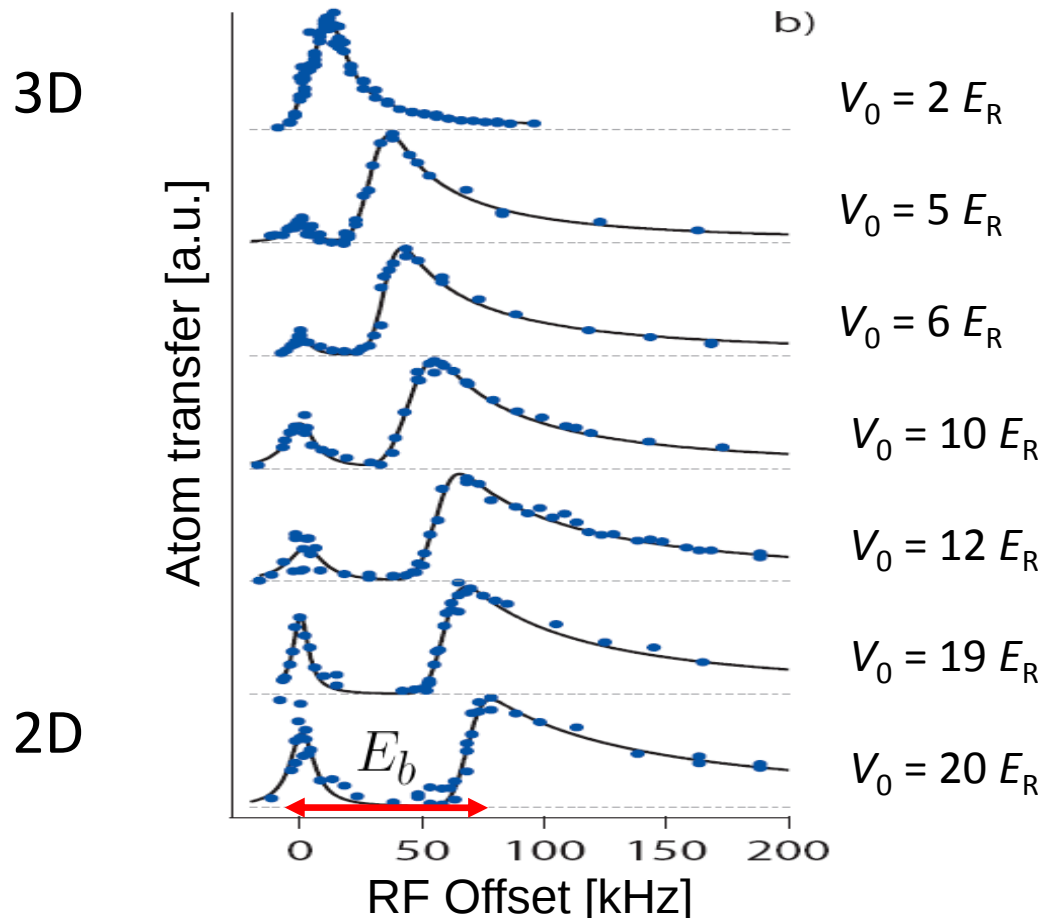
Evolution of Fermion Pairing from 3D to 2D



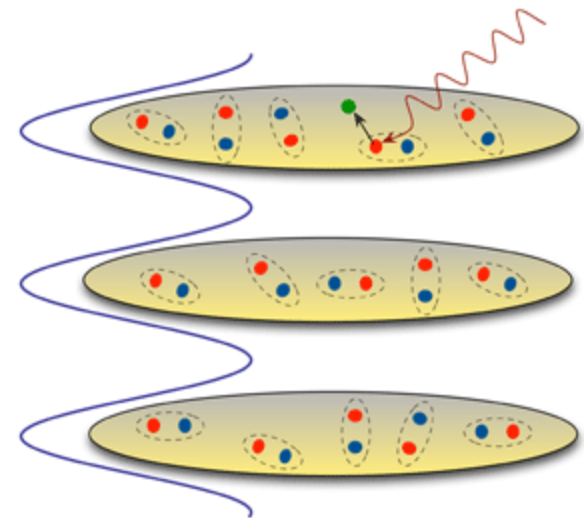
Ariel T. Sommer, et al, *Phys. Rev. Lett.* **108**, 045302 (2012)

Density of States: 3D $\sim \sqrt{\epsilon}$
2D *const.*

Direct consequence:
Always a bound state in 2D

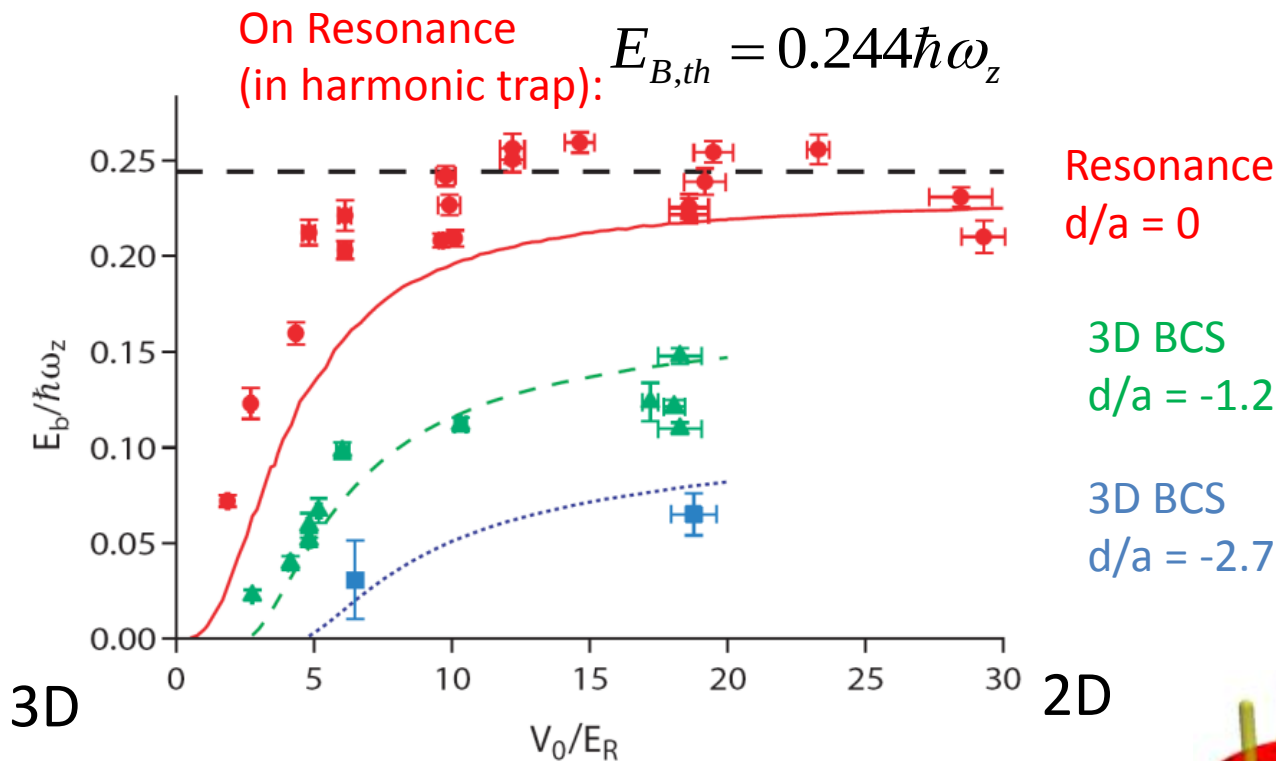


RF spectroscopy:





Evolution of Fermion Pairing from 3D to 2D



- Observed fermion pairing from 3D to 2D
 - Are those pairs superfluid?
 - Study coherence, thermodynamics, rotation...
 - What is T_C as a function of interlayer tunneling?

Towards a recipe for high T_C

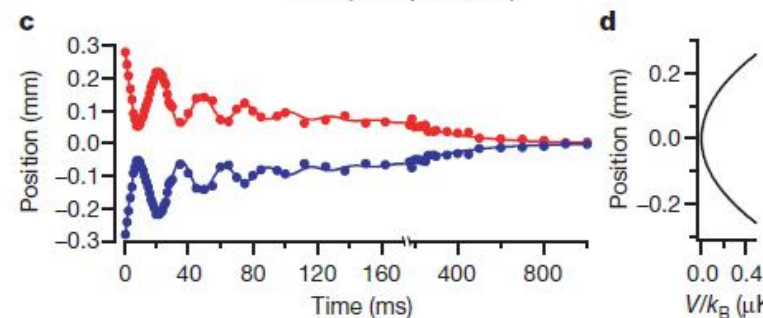
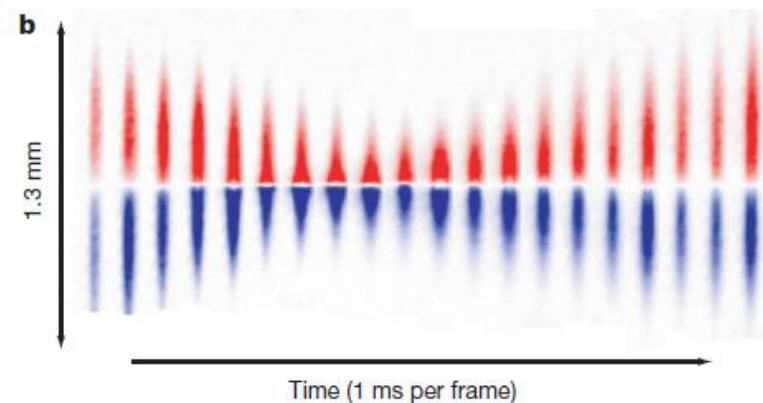
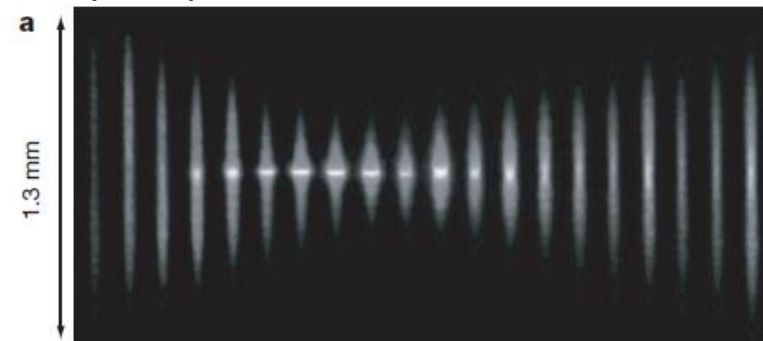
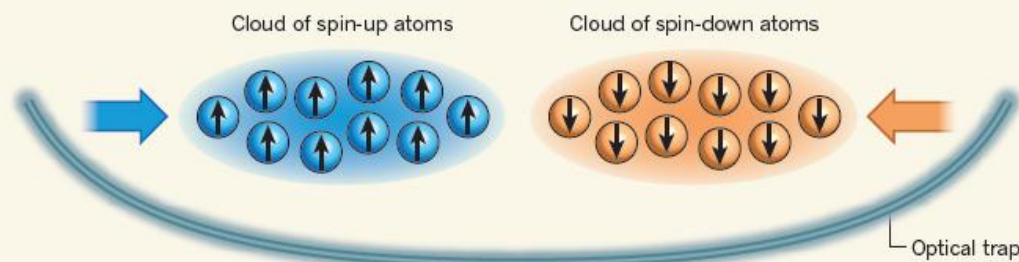




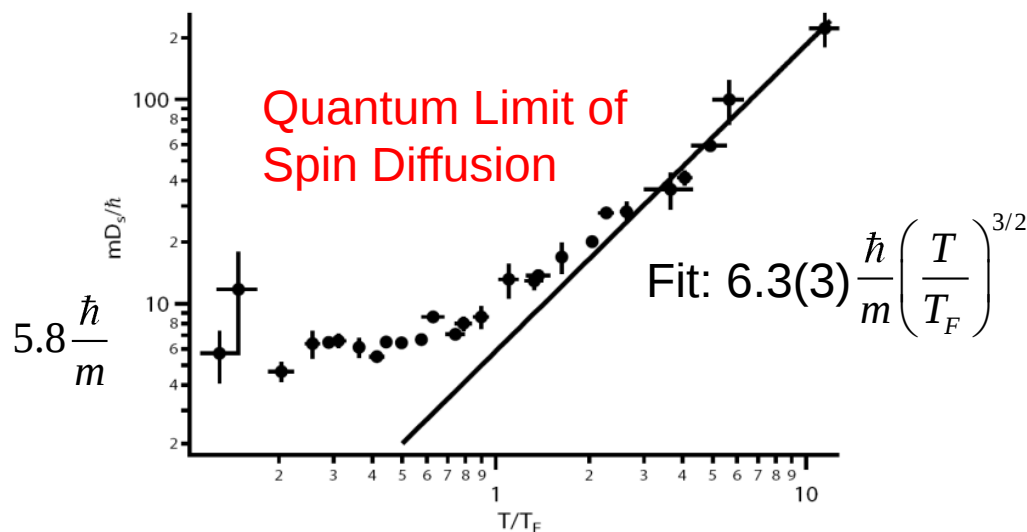
Spin Transport – “Little Fermi Collider” (LFC)



Ariel Sommer, *et al*, *Nature* **472**, 201 (2011)



Spin Diffusion vs. Temperature





Thermodynamics of the Strongly-Interacting Fermi Gas

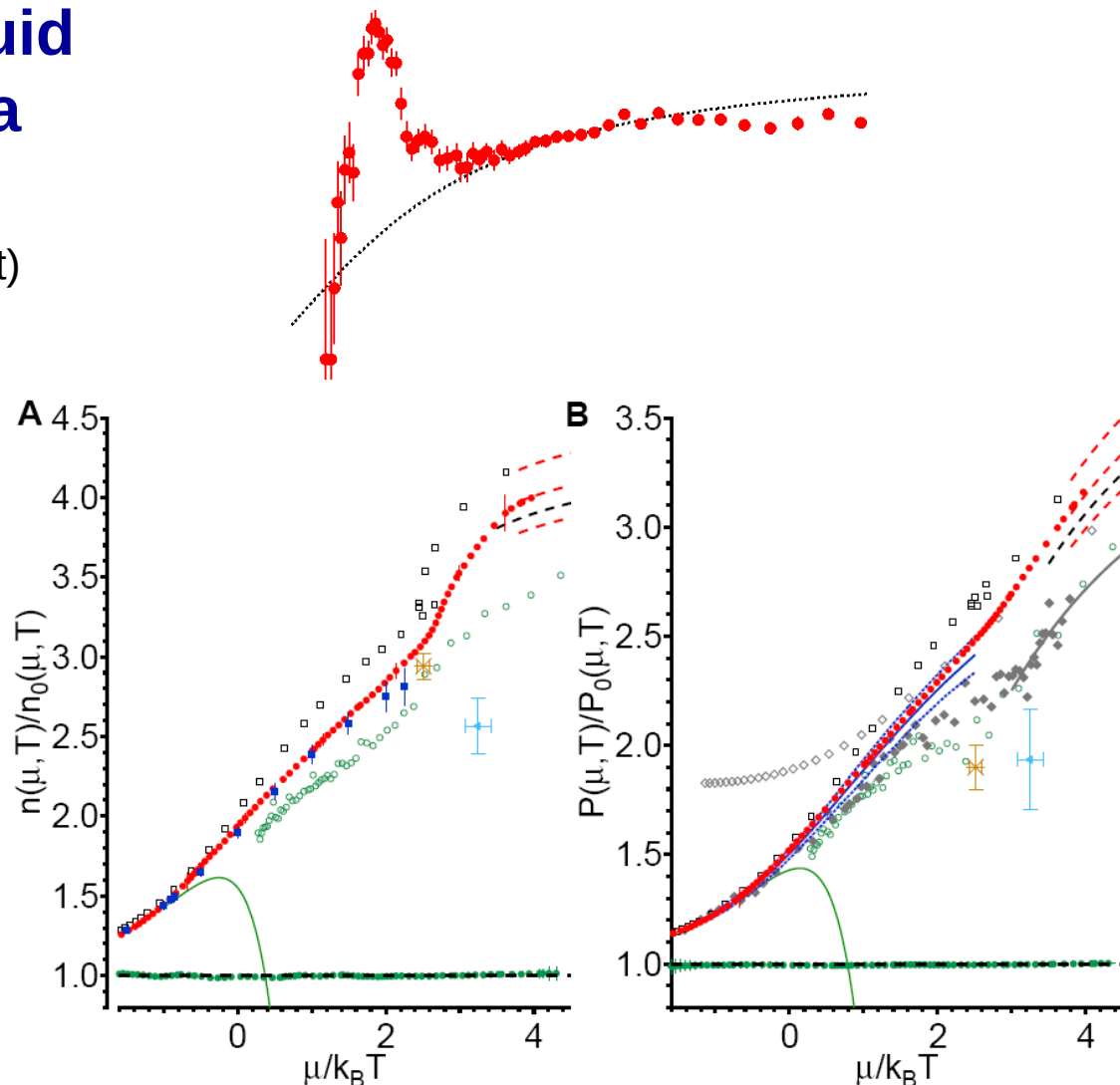


Revealing the Superfluid Lambda Transition in a Fermi Gas

Mark J.H. Ku, *et al*, *Science* (in print)

“Feynman diagrams versus Feynman quantum emulator”

K. Van Houcke, *et al* (submitted to *Nature Physics*)





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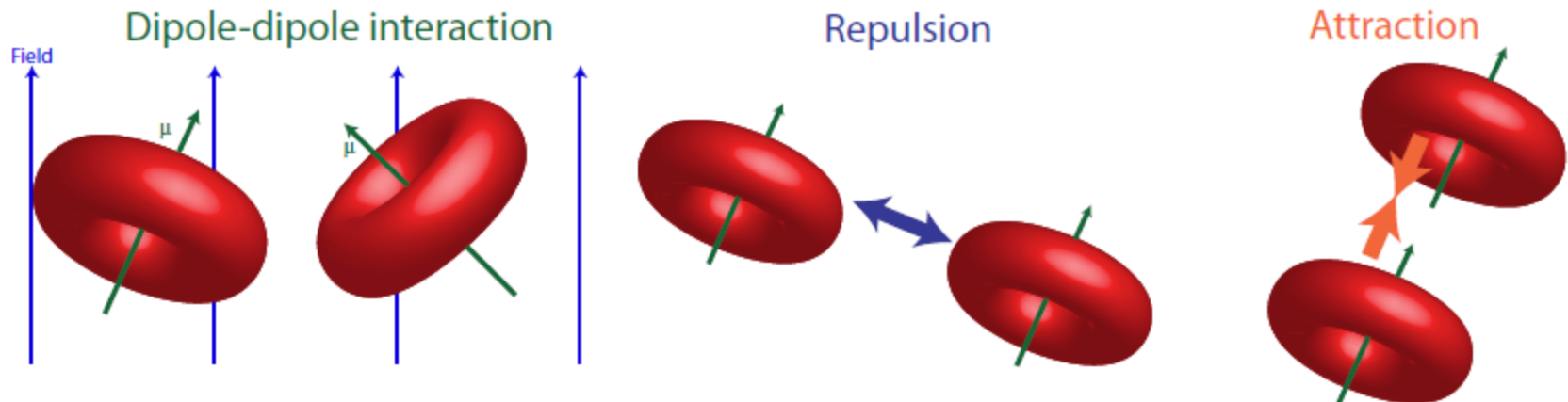


Ultracold Dipolar Physics



- Exploit strong, long-range r^{-3} , and anisotropic dipole-dipole interaction

$$V_d(r) = \frac{d^2}{r^3} (1 - 3 \cos^2 \theta)$$





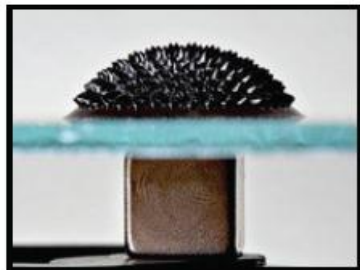
Ultracold dipolar Bose and Fermi gases: Exotic quantum phases



Traps

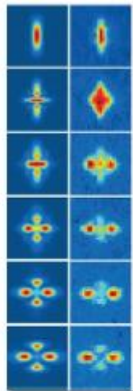
Bosons

Trap distortions, instabilities
spinors



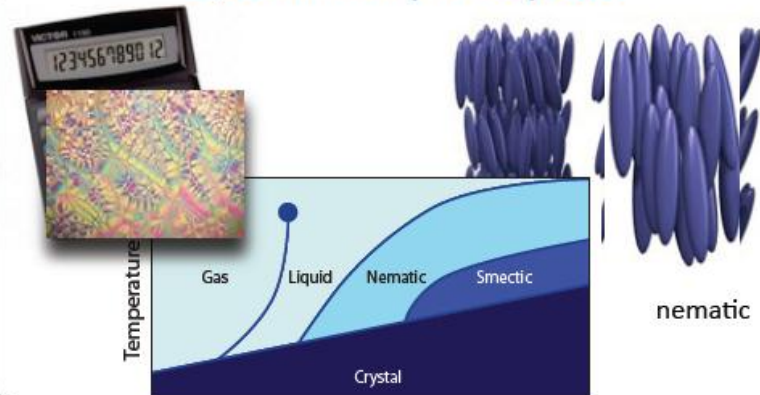
Quantum ferrofluids

⁵²Cr.
Pfau, et al. '08



Fermions

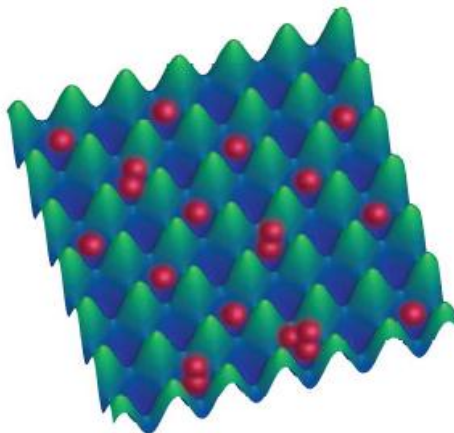
Quantum liquid crystals



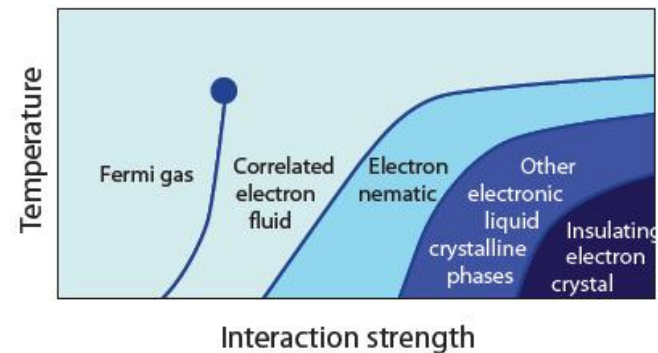
nematic

Lattices

Density waves and supersolids



Lattice quantum liquid crystals



E. Fradkin, S. A. Kivelson, &
V. Oganesyan, Science '07



Laser cooling Dysprosium



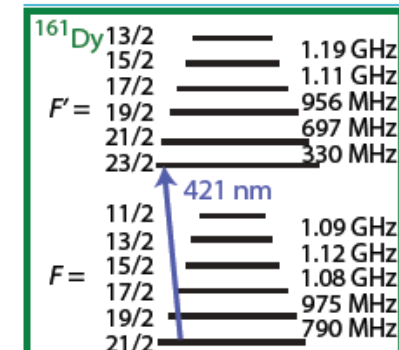
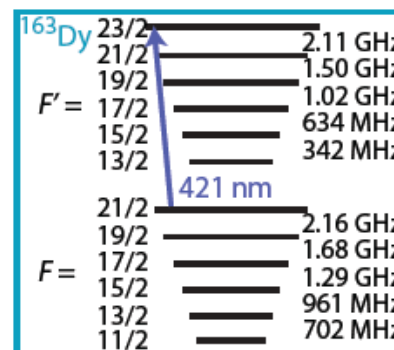
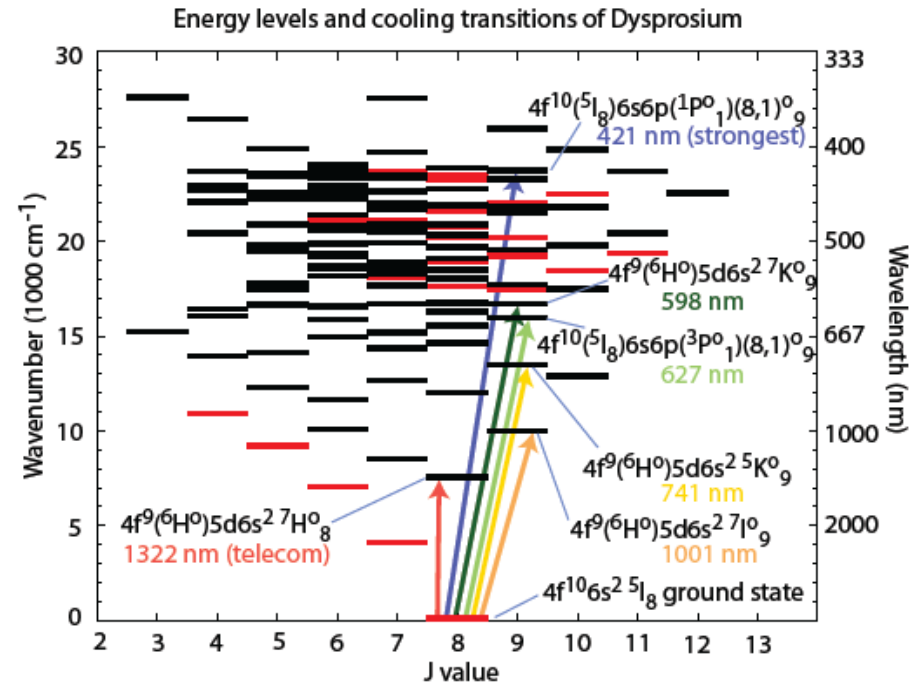
Periodic Table of the Elements

1	2																	18																																																																					
3	4																	19	20																																																																				
5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30																																																														
31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118

* Lanthanide Series
+ Actinide Series



$\mu = 10 \mu_B!$
 $Rb: 200 \times \mu^2 m$
 $Cr: 9 \times \mu^2 m$



Five isotopes, 3 bosons ($I=0$), 2 fermions ($I=5/2$)

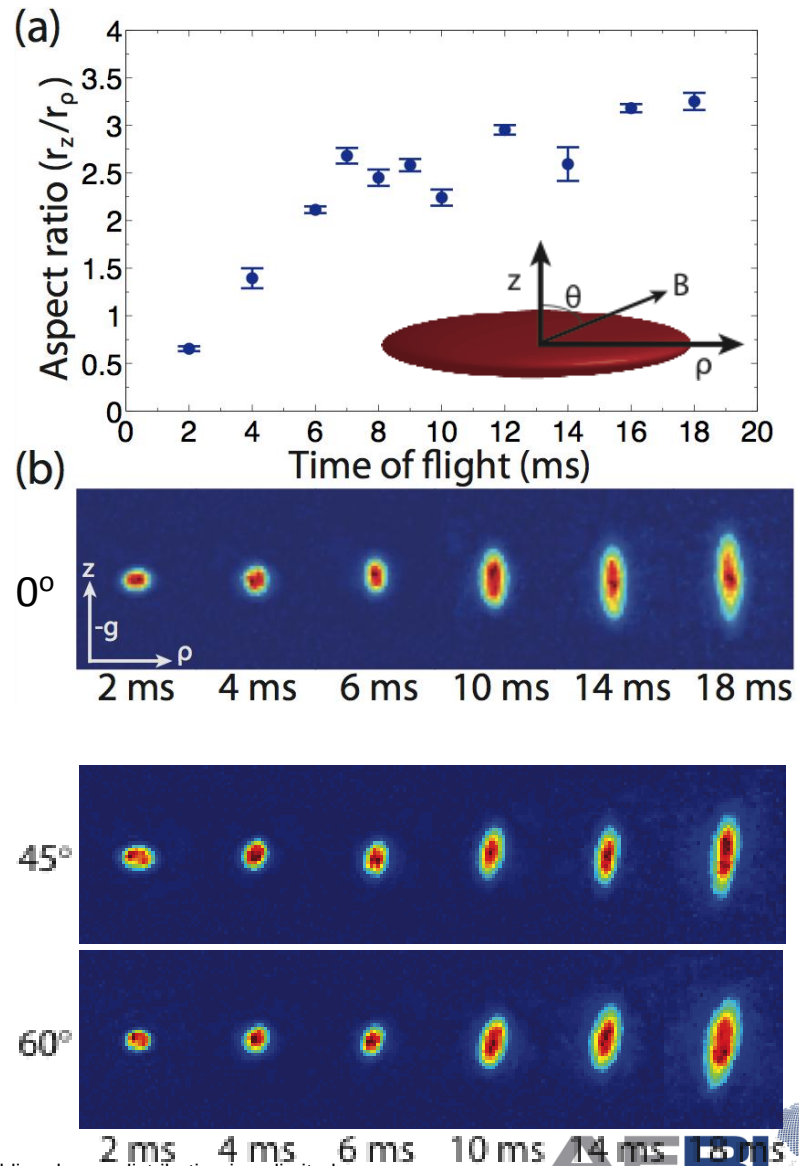
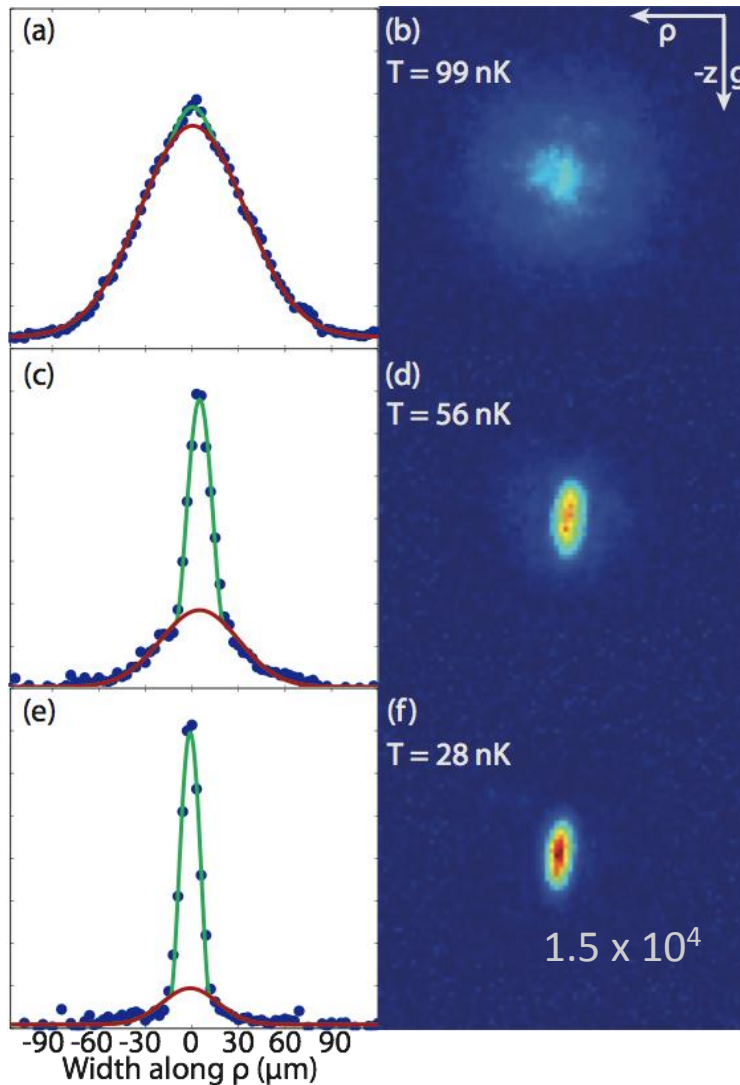


Strongly Dipolar Dy BEC

M. Lu, N. Burdick, S.-H. Youn, and B. Lev, *Phys. Rev. Lett.* 107 190401 (2011)



BECs of ^{164}Dy and ^{162}Dy



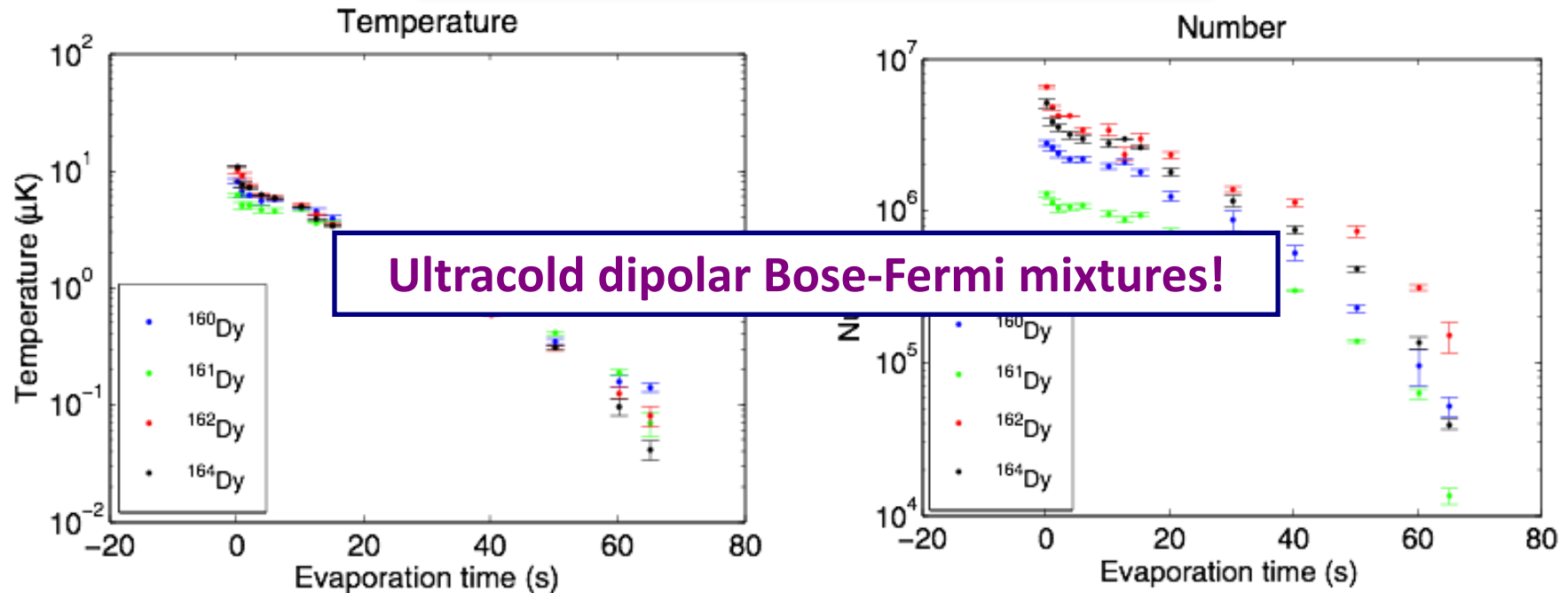
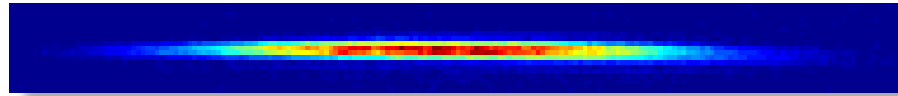


Evaporative cooling of all isotopes

Including identical fermions! $T/T_F = 1.3$ in crossed ODT



Single beam ODT



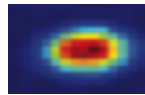
Universal dipolar scattering?

Bohn, Cavagnero, Ticknor, New J. Phys. '09



First dipolar degenerate Fermi gas!

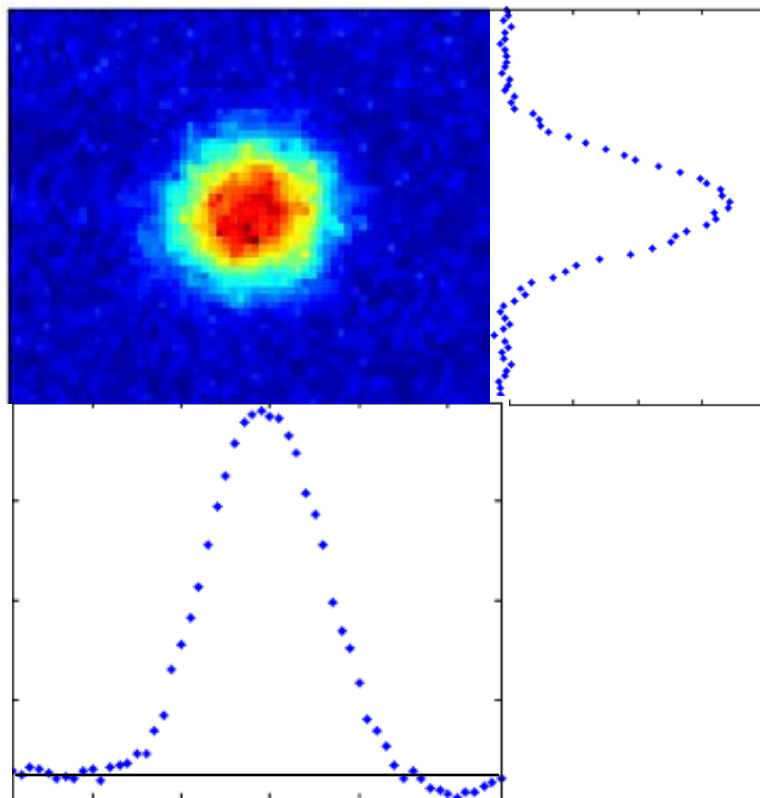
^{161}Dy Sympathetically cooled with ^{161}Dy to $T/T_F < 0.3$



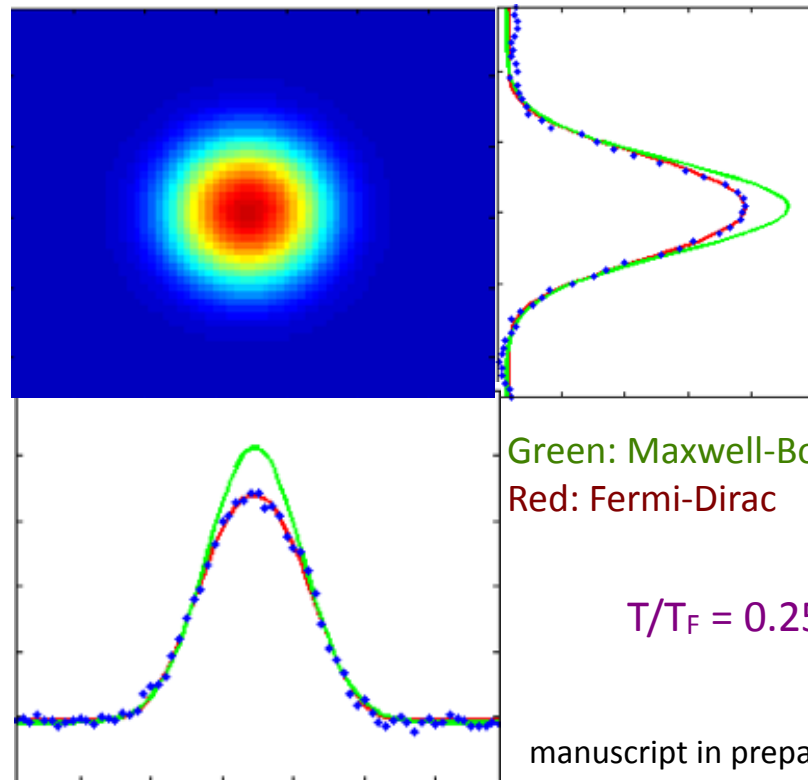
Oblate initial trap

Fermionic ^{161}Dy time-of-flight expansion

Single shot: 6×10^3 atoms



Average of three shots



Green: Maxwell-Boltzmann
Red: Fermi-Dirac

$T/T_F = 0.25$

manuscript in preparation



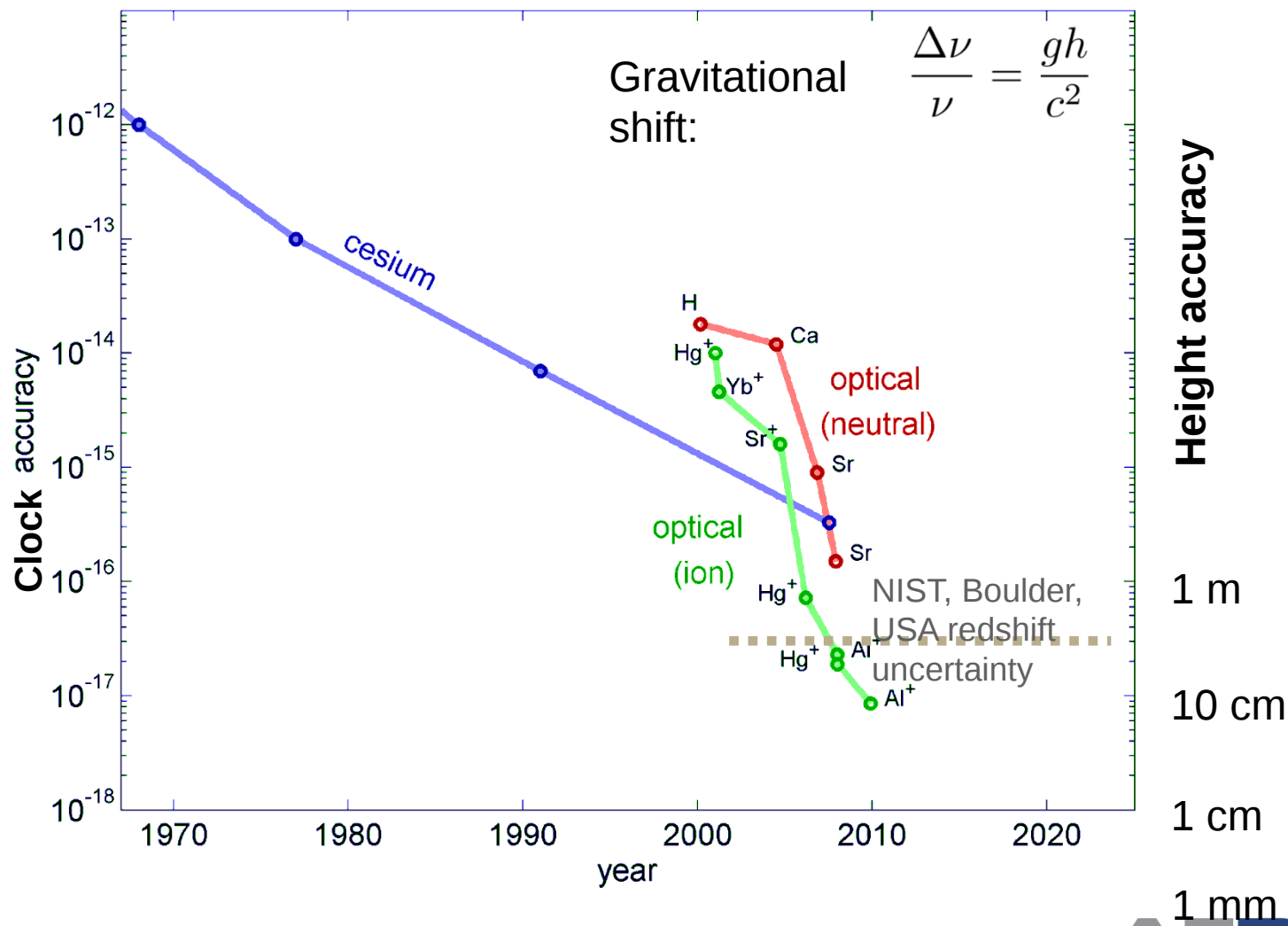
Outline



- **Quantum Simulation, Strongly-Interacting Quantum Gases**
 - **Bosons: Markus Greiner, Harvard (MURI)**
 - **Algorithmic Cooling in Quantum Gases**
Waseem Bakr, *et al*, *Nature* **480**, 500 (2011)
 - **Quantum Magnetism**
Jonathan Simon, *et al*, *Nature* **472**, 307 (2011)
 - **Fermions: Martin Zwierlein, MIT (PECASE, MURI)**
 - **Evolution of Fermi Pairing from 3D to 2D**
Ariel T. Sommer, *et al*, *Phys. Rev. Lett.* **108**, 045302 (2012)
 - **Spin Transport in a Strongly-Interacting Fermi Gas**
Ariel Sommer, *et al*, *Nature* **472**, 201 (2011)
 - **Thermodynamics of a Unitary Fermi Gas: Superfluid Lambda Transition**
Mark J.H. Ku, *et al*, *Science* (in print); K. Van Houcke, *et al* (submitted to *Nature Physics*)
- **Dipolar Matter: Benjamin Lev, UIUC/Stanford (YIP)**
 - **Dy BEC, and First Dipolar Degenerate Fermi Gas**
Mingwu Lu, *et al*, *Phys. Rev. Lett.* **107**, 190401 (2011)
- **Quantum Metrology: Till Rosenband, NIST**
 - **Coherent Drive Spectroscopy**
D.B. Hume, *et al*, *Phys. Rev. Lett.* **107**, 243902 (2011)

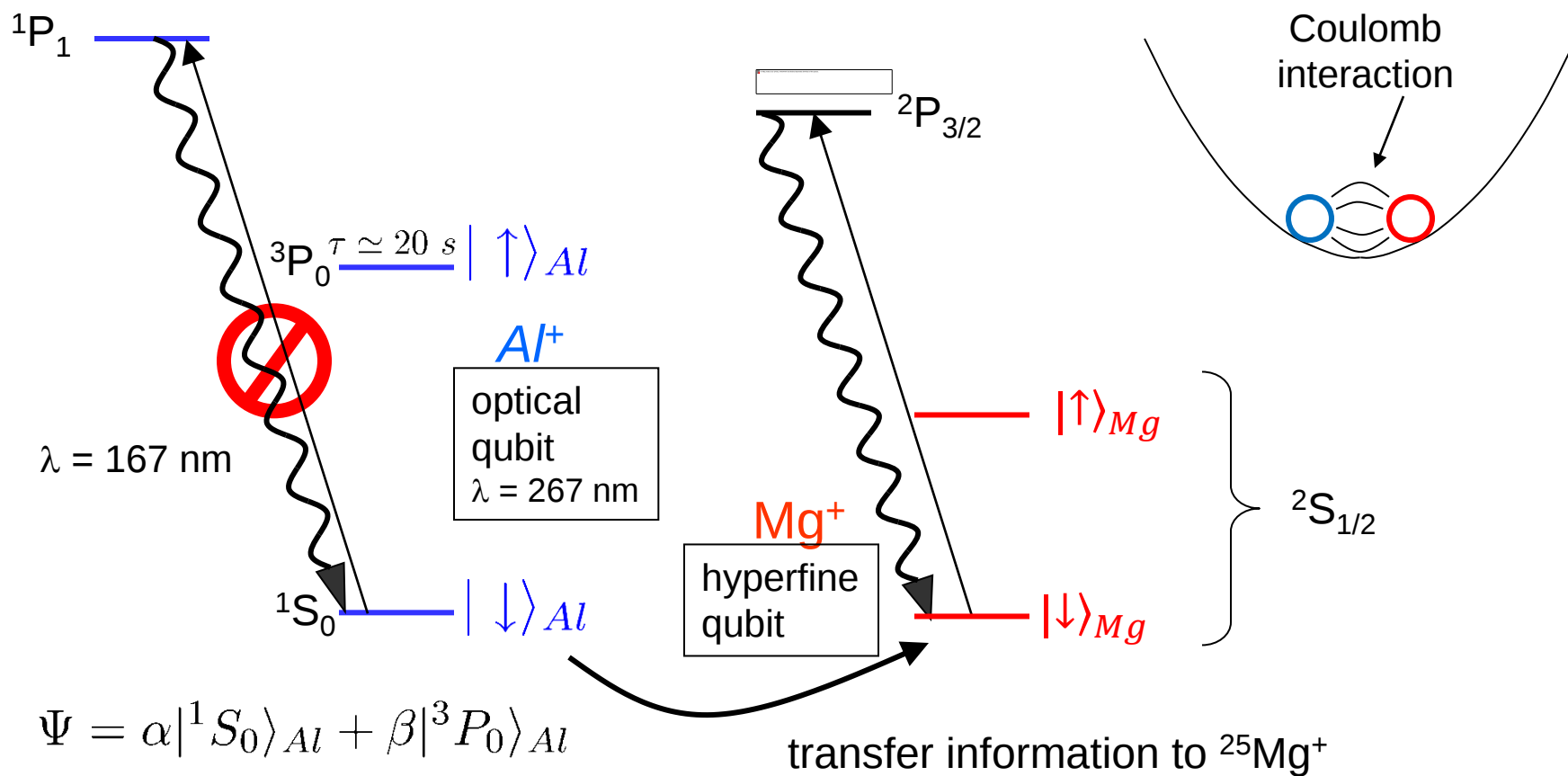


Motivation: Al^+ clock accuracy



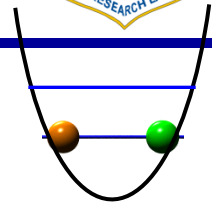


Quantum Logic Spectroscopy



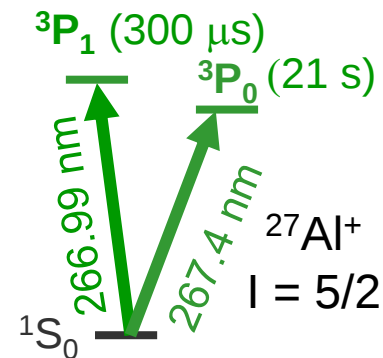
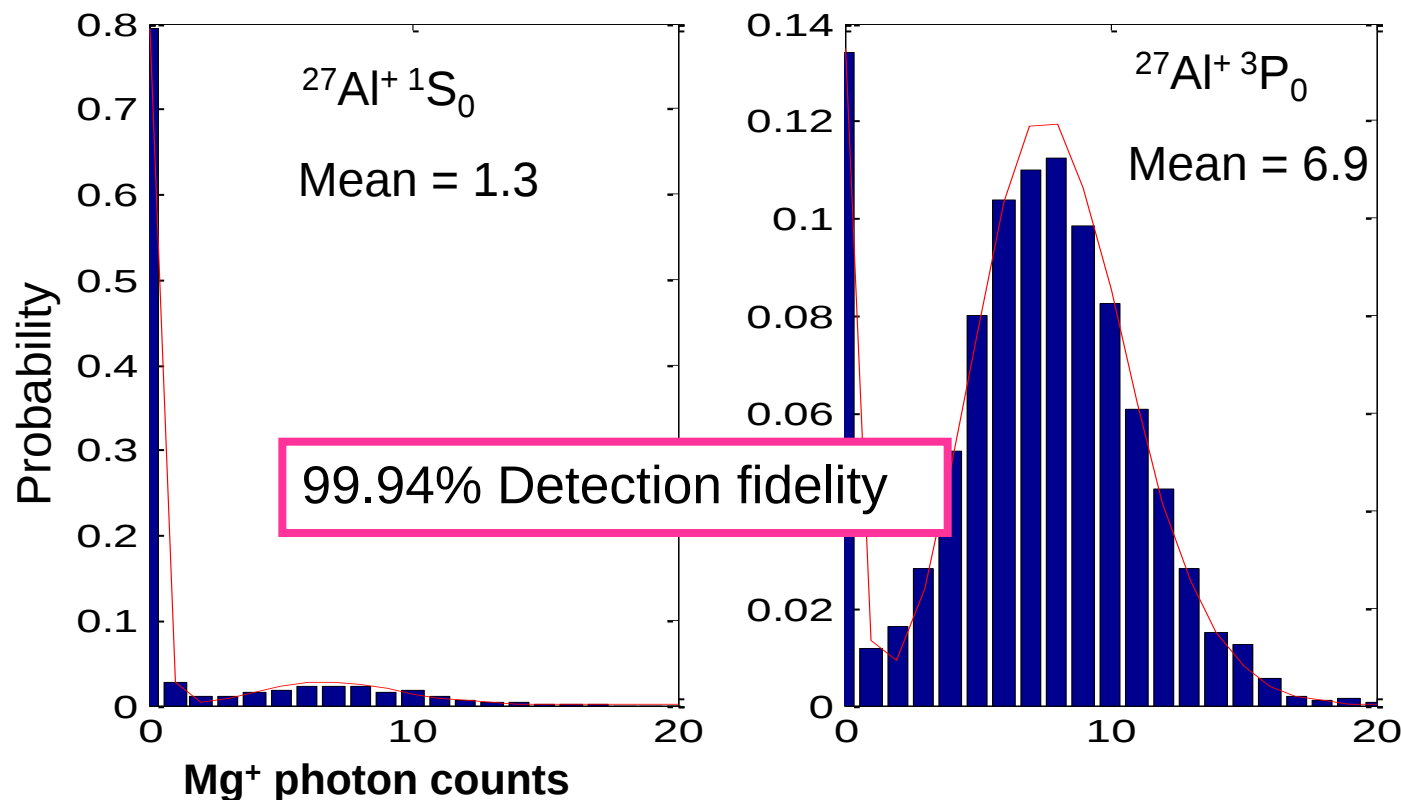


Al⁺ quantum-logic spectroscopy



1. Cool to motional ground-state with Mg⁺ (Raman cooling)
2. Depending on Al⁺ clock state, add one vibrational quantum via 1S_0 - 3P_1
3. Detect vibrational quantum with Mg⁺

QND



P.O. Schmidt, *et al.*
Science **309**, 749 (2005)

D. B. Hume, *et al.*
PRL **99**, 120502 (2007)

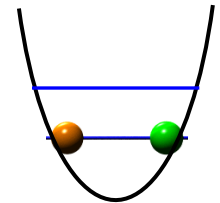


Al⁺ coherent-drive spectroscopy

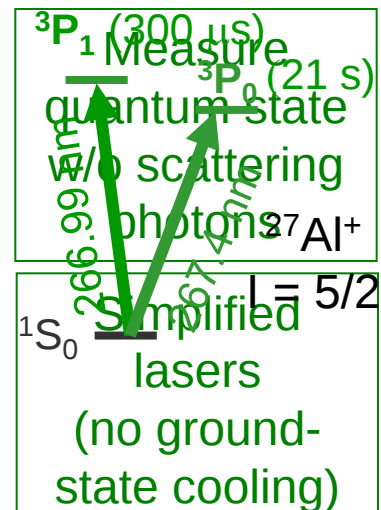
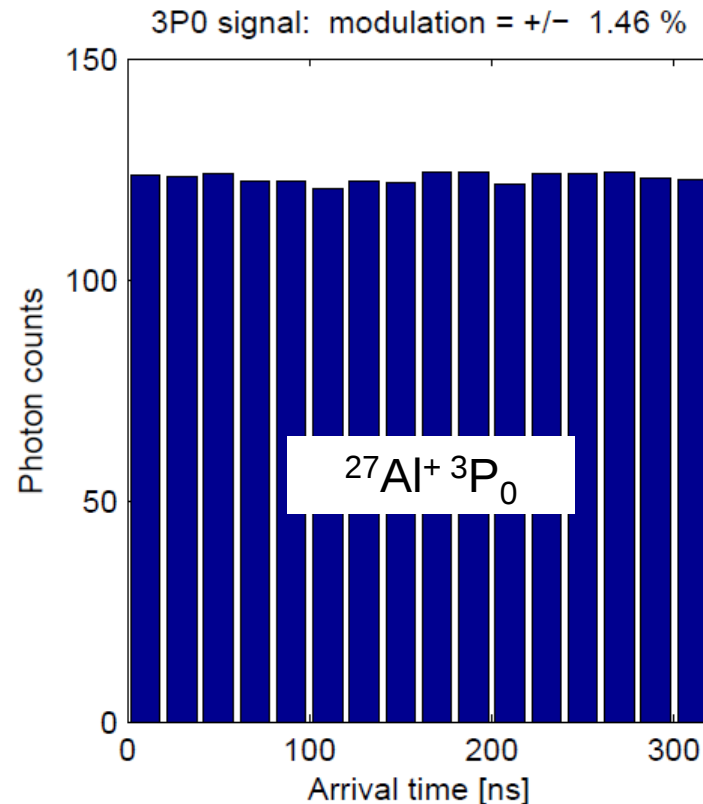
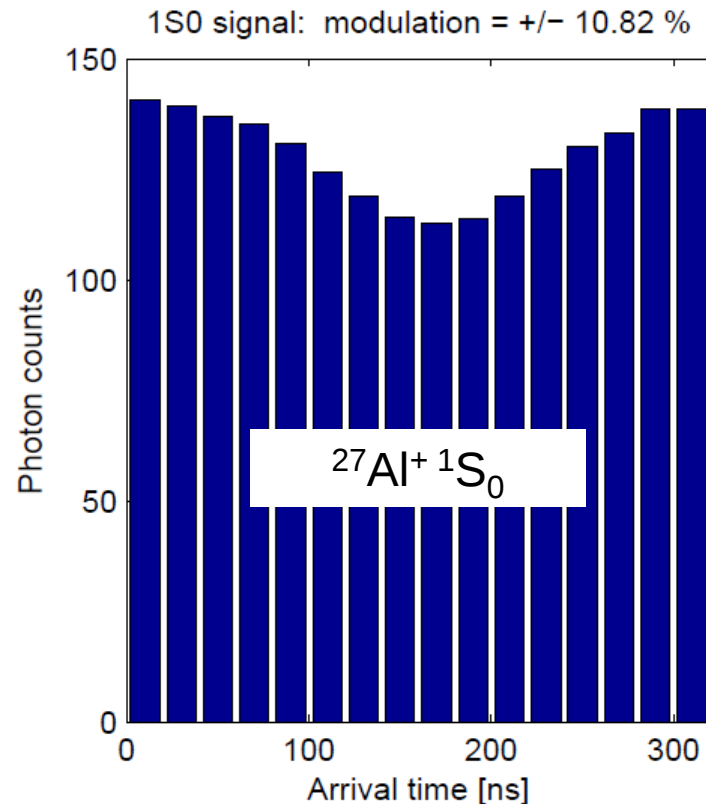


Mg⁺ Doppler

- ~~Cool to motional ground state with Mg⁺ (Raman cooling)~~
- drive coherent motion
- Depending on Al⁺ clock state, ~~add one vibrational quantum~~ via 1S_0 - 3P_1
3. Detect ~~vibrational quantum~~ with Mg⁺ coherent motion



D. B. Hume, et al.
PRL 107, 243902 (2011)



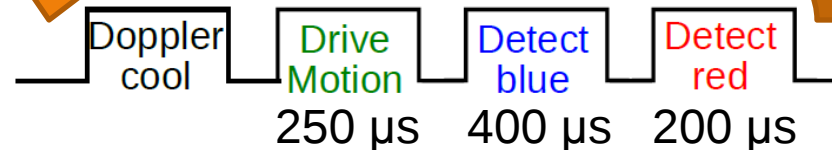
Slower



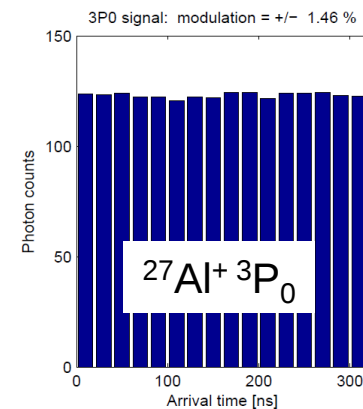
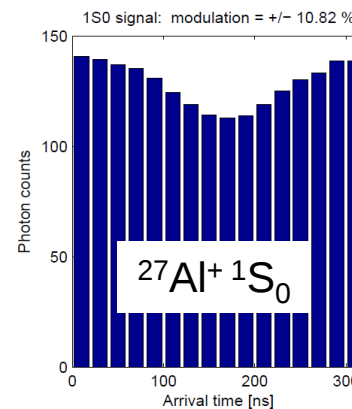
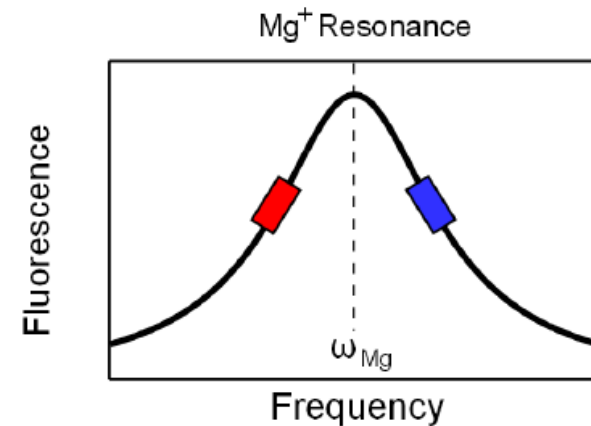
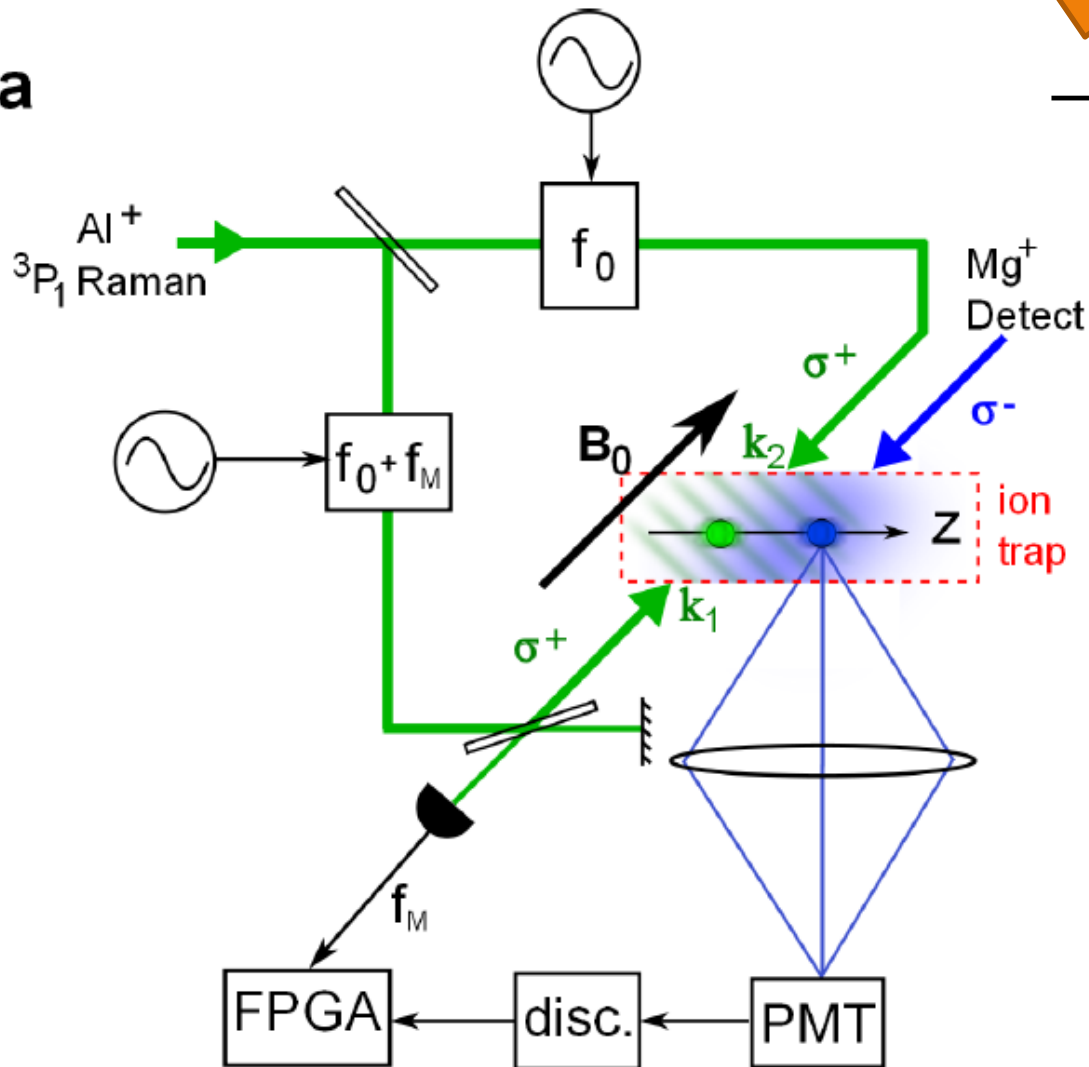
Al⁺ coherent-drive spectroscopy



D. B. Hume, et al., PRL107, 243902 (2011)



a

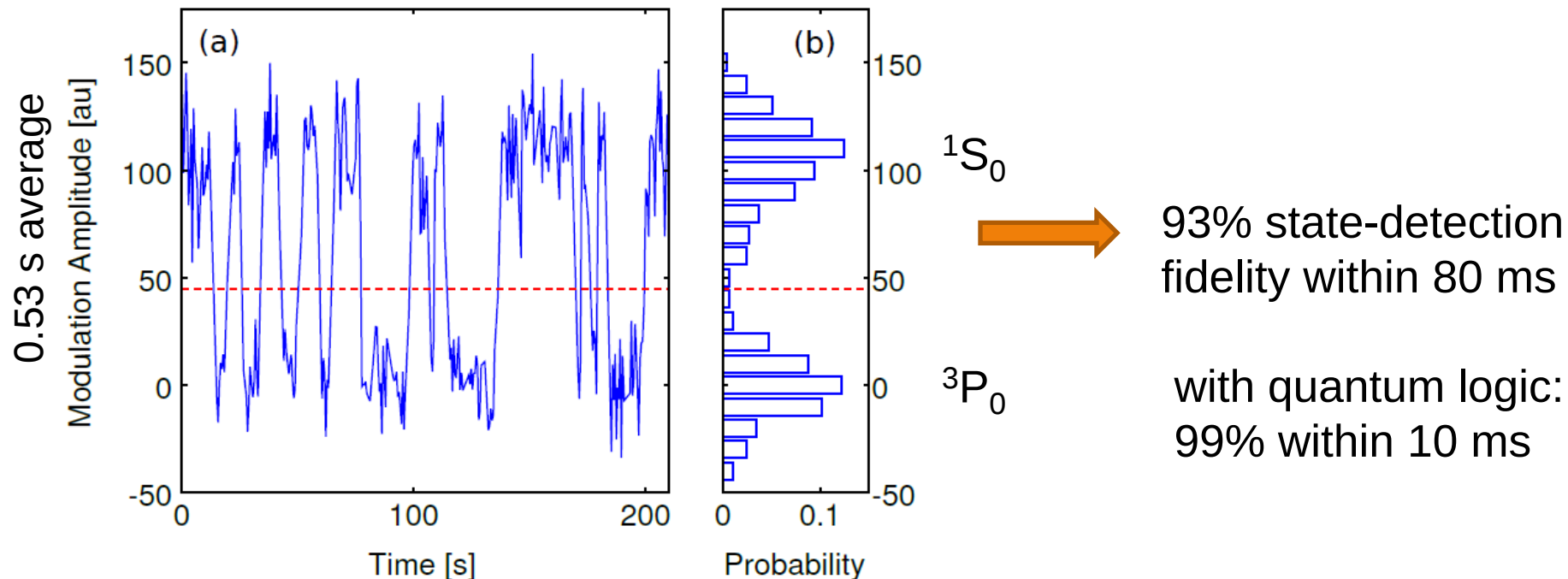




Quantum Jumps



Quantum jumps between clock states (1S_0 and 3P_0)



- Coherent drive detection rate could be improved by higher modulation amplitude or photon collection efficiency
- Can be generalized for more than one Al^+ ion



Interactions with Other Agencies



Agency/Group	POC	Scientific Area
ARO	Peter Reynolds Paul Baker	Cold Quantum Gases (CQG)
	TR Govindan	Quantum Information Science (QIS)
	Rich Hammond	Ultrafast/Ultraintense Phenomena (UUP)
ONR	Charles Clark	CQG, QIS
	Ralph Wachter	QIS
DARPA	Jamil Abo-Shaeer	CQG, QIS
	Jag Shah	QIS
	Matt Goodman	QIS
NSF	Wendell Hill	CQG, QIS, UUP
DoE	Jeff Krause	CQG, UUP
IARPA	Michael Mandelberg	QIS
QISCOG	>20 program managers from ~10 agencies/institutions	QIS

Thank you